Demonstration of a Diesel Fuel-Borne Catalyst System and Low NO_x Control Technology for Reducing Particulate and NO_x Emissions

Final Report

96-334

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Abstract

Arthur D. Little, Cummins Engine Company, and Rhodia Rare Earth's performed a project to demonstrate a fuel-borne catalyst system and low NO_x control technology for reducing particulate and NO_x emissions from on-road diesel engines. The system developed was a combination of cooled, exhaust gas recirculation (EGR) coupled with a diesel particulate filter. Cerium catalyst was added to the diesel fuel to assist in filter regeneration. The system was applied to the Cummins B Series (5.9L ISB) diesel engine.

Considerable development work was required before a working system could be demonstrated. The filter system initially focused on a compact, low volume silicon carbide design. This system was emissions tested and then installed in a UPS package car for demonstration in Southern California. The system was able to achieve NO_x levels of 2.5 g/bhp-hr and particulate of 0.03 g/bhp-hr over the transient heavy-duty test cycle. Checkout testing prior to entering UPS service indicated filter face plugging. Cummins and Rhodia investigated the reasons for this plugging and tested several alternative filter options. This testing indicated that filter face plugging occurred as a result of unburned fuel during engine restarts and using a high cell density filter (300 cells per square inch). Tests showed reducing the filter density eliminated face plugging. A HJS metallic filter with wide frontal area openings was found to be acceptable, albeit not optimized for the application.

The UPS package car operated with the EGR engine alone for 8 months accumulating over 16,000 trouble free miles. The HJS equipped system operated in UPS service for an additional 2 months and accumulated 6,000 miles. Based on the experience obtained in this project, it appears that a combination system of cooled EGR, cerium catalyst in diesel fuel, and particulate filter is feasible for reducing NO_x and PM emissions in heavy-duty diesel vehicles. However, considerably more work is necessary to commercialize such a system and to make sure that filter regeneration occurs reliabily over all vehicle-operating modes.

1. Executive Summary

The objective of this work was to demonstrate vehicle and emissions performance of an advanced diesel engine achieving low NO_x and particulate (PM) emissions. Arthur D. Little, teamed with Rhodia and Cummins, proposed a cost-shared project to the SCAQMD and the ARB to develop and demonstrate, in vehicle applications, an EGR engine using Rhodia's cerium-based fuel additive and a particulate filter. The tradeoff of reducing NO_x and PM is well known for diesel engines, and the concept proposed to reduce NO_x with cooled EGR and to use a filter to trap the increased exhaust particulate. The Rhodia cerium-based catalytic diesel fuel additive was chosen to ensure filter regeneration by lowering the filter regeneration temperature. Rhodia had demonstrated their additive-filter technology in Europe, and had worked with Cummins on similar filter systems. What was new in this project was developing an engine system for both low-NO_x and low-PM emissions performance. Cummins selected their B Series, 5.9L diesel engine for this project.

The scope of the project was to select a host site, demonstrate the engine system by integrating the system on host site vehicles and operating the vehicles for 12 months. Part of the demonstration included performing emissions tests to characterize the performance of the advanced diesel engine exhaust, and developing a report on the results of the project. The host site selected for this project was United Parcel Service (UPS). The San Bernardino UPS depot (located in the South Coast Air Basin) was selected for demonstrating the advanced diesel systems. This site was the best compromise of daily mileage, duty cycle, fleet size, central fueling, and heavy-duty vehicle use.

Cummins and Rhodia selected a 5.9L diesel engine equipped with Rhodia's cerium and 3L Ibiden silicon carbide diesel particulate filter (DPF), in conjunction with high-rate cooled EGR, to achieve low rates of both NO_x and PM. Cummins equipped a 1998 ISB5.9 engine with an electronically controlled, cooled EGR system, a 3L Ibiden silicon carbide trap, and Rhodia's EOLYS fuel-borne cerium catalyst. The trap had a cell density of 300 cells/in^2. Cummins optimized the system to achieve low emissions and provide good engine response.

This engine was installed in a heavy-duty package car owned by UPS. Rhodia was responsible for installing and demonstrating the cerium dosing system on the package car. In checkout testing at Cummins, the particulate filter exhibited rapid and severe face plugging, the cause of which was unburned fuel depositing on the trap face during starts. This resulted in a system that was not road worthy, and the cerium filter system was removed from the package car, the dosing system disabled, and the vehicle returned to UPS for regular service using only the EGR engine.

Cummins and Rhodia investigated a number of different systems to overcome the face plugging issue. Electrically heated, dual filters were successfully demonstrated at Cummins in a Dodge Ram medium-duty pickup, but this system also experienced face plugging when installed on the UPS package car. Several additional concepts were tried on the Cummins test vehicle until it became clear that face plugging was caused by unburned fuel during engine starting. Plugging was more severe with number of restarts and higher cell densities. A metallic filter with wider initial cell openings was installed on the package car and operated for a limited period without face or filter plugging.

Analyses of the various filter systems indicated that UPS's unique duty cycle was also a contributor to face plugging. Typical of UPS service, the vehicle is driven several miles at highway speeds to its delivery area. The vehicle then makes anywhere from 70 to 100 stops to unload and load parcels. At each stop the engine is shut down and restarted, resulting in some 70 to 100 warm restarts per day. It was these restarts where the engine is overfueled to start that caused filter face plugging. This was solved by effectively decreasing the cell density of the filter.

The UPS test vehicle accumulated approximately 29,000 miles with the test engine. Approximately 6,000 miles were accumulated with a particulate filter system in place, and 23,000 miles with no filter system. During field testing, the engine performed well and required only normal scheduled maintenance. The test vehicle's average fuel economy was 8.8 mi/gal. This was substantially better than the control vehicle's fuel economy of 6.3 mi/gal. Most of this difference is attributable to design improvements associated with the test vehicle's 1998 ISB5.9 engine platform, over the control vehicle's 1996 mechanical B5.9.

Due to problems with filter face plugging, the only emissions testing completed was engine dynamometer testing using the Federal Test Procedure (FTP) for heavy-duty engines. The FTP results for the Cummins 5.9L equipped with cooled EGR using Rhodia's cerium based fuel additive, and a 3L Ibiden filter show good NO_x and PM performance. In g/bhp-hr, NO_x was 2.53, hydrocarbons 0.12, and PM <0.03. This compared to the baseline diesel emissions of 3.78 g/bhp-hr NO_x, 0.15 g/bhp-hr HC, and 0.1 g/bhp-hr PM. Planned chassis testing and assessment of unregulated emissions as well as PM characterization was not performed. Rhodia provided additional test information, however, on European engines using the cerium fuel additive and filter system that confirmed that PAHs are reduced (60 to 90 percent) and the emission of polychlorinated dibenzodioxins/furans was not found to be higher with the use of the cerium additive.

With careful matching of trap characteristics to the vehicle application and system integration, the combination of cooled EGR, EOLYS fuel-borne catalyst, and a particulate filter is feasible for reducing NO_x and PM emissions in heavy-duty diesel engines. However, considerably more engineering is needed to demonstrate the viability of this system and have it operate over all engine and vehicle operating conditions. The biggest drawback to the technology is that the trap will not regenerate reliably in some operating modes, especially in primarily stop-and-go conditions. Under these conditions, fairly frequent and sustained intervals of high engine loads are needed to initiate regeneration. Improved engine fuel management and EGR system control are needed to reduce trap plugging. The EOLYS system does lower the soot oxidation temperature, and favors uniform oxidation throughout the DPF.

2. Project Background and Objectives

Particulate filters using wall-flow monolithic filters are capable of reducing diesel soot emissions by 85 percent or more. As the soot accumulates in the trap, the trap's flow resistance increases and compromises engine performance. Particulate filters must be periodically *regenerated* by burning this accumulation in order to remain functional over time. Diesel exhaust contains sufficient oxygen to burn the soot; however, in the absence of a catalyst, temperatures of approximately 500°C are needed periodically. Such a high temperature is rarely maintained in diesel exhaust, so supplemental heat sources, such as a burner or an electric heating element, have been previously used to initiate regeneration. Adding these external heat sources tends to make particulate filter systems complex and unreliable. Applying catalysts to the surfaces of the filter is effective in reducing the minimum regeneration temperature to approximately 400°C. The drawback of this technology is that if the driving condition leads to a complete coverage of the catalyst bed by unburned soot, the catalyst active sites are no longer accessible and catalyzed regeneration will not occur. Additionally, catalysts tend to be rapidly deactivated in diesel exhaust, due to sulfur poisoning. These phenomena led researchers to investigate the use of fuel-borne catalysts as a means of continually replenishing the trap with active catalysts.

Rhodia Rare Earth's is an international chemical company headquartered in France. Over the last decade, Rhodia has developed and tested a diesel fuel additive that allows diesel particulate traps to regenerate without an external heat source, such as a burner or electric heating element. The catalyst's active ingredient is cerium, in the form of a liquid organo-metallic compound that is miscible in diesel fuel. The cerium-containing compound is effective when mixed with diesel fuel at cerium concentrations between 25 and 100 ppm. In the combustion chamber, the additive is burned along with the diesel fuel, where the cerium compound is oxidized to ceria (CeO_2), allowing mixing of the ceria catalyst and soot particles. Used in conjunction with a particulate trap, the additive has been shown effective in promoting reliable regeneration of the trap. The ceria is captured and retained in the trap at high collection efficiency even during regeneration (>99.5%).[1,2]

During 1989-1991, Rhodia[3], together with NGK and Corning, demonstrated particulate filters with the fuel-borne catalysts in 110 diesel transit buses in Athens, Greece. Each bus accumulated over 100,000 km over two years. Particulate was reduced by 80 percent, and the traps captured 94 percent of the ceria. The remaining 6 percent were shared between trapping in the lube oil (3 to 4 percent) and as a coating in the exhaust line (2 to 3 percent). Corning and NGK filters have demonstrated a trapping efficiency

[1] Khair, M., J. Lemaire, and S. Fischer, *Achieving Heavy-Duty Diesel NO_x/PM Levels Below the EPA 2002 Standards – An Integrated Solution,* SAE 2000-01-0187.

[2] Czerwinshke, J., T. Mosimann, and U. Matter, *Comparison of the Engines Liebherr I (86) and Liebherr II (96) with Particulate Trap, with Fuel Additives and with Detailed Analysis of the Particulate Emissions,* Report 7, Verminderung der Emissionen von Realmaschinen im Tunnelbau (VERT), June 1997.

[3] The work was performed by Rhone-Poulenc Corporation prior to the time that it spun-off its rare earth chemical business under the name of Rhodia Rare Earth's.

of ceria particles >99.5 percent using European test procedures, proving that no ceria is released by the trap. In the mid-1990s, Rhodia began marketing its cerium fuel-borne catalyst under the brand name "EOLYS."

Based on the successful experience in Athens, Cummins Engine Company subsequently investigated the performance of the EOLYS catalyst in a 1996 B5.9 engine equipped with a particulate filter. The engine was not equipped with EGR. The engine and trap system were installed and tested in a medium-duty Dodge Ram pick-up truck. The fuel-borne catalyst performed well in this application.

In Model Year (MY) 1998, Cummins Engine Company introduced the ISB, an updated version of the B5.9, equipped with electronic controls, an improved head, and uncooled EGR. During the mid-1990s, Cummins investigated cooled EGR as a means of achieving lower NO_x levels than those achievable with uncooled EGR. Because EGR tends to elevate PM rates to above the applicable 0.10 g/bhp-hr standard, combining cooled EGR with a particulate filter regenerated with EOLYS catalyst appeared to be a promising approach to achieving simultaneously low levels of NO_x and PM in medium-heavy-duty diesel engines.

In May 1997, Acurex Environmental Corporation[4] proposed to the SCAQMD to demonstrate cooled EGR, the EOLYS catalyst, and a particulate filter in two vehicles equipped with Cummins B5.9 engines. On June 27, 1997, SCAQMD and Acurex Environmental executed SCAQMD Contract No. 97140, authorizing Acurex Environmental to proceed with the proposed demonstration. The project was funded and managed jointly by the SCAQMD and the ARB. Cummins Engine Company was a major project subcontractor, and Rhodia Rare Earth's contributed substantial resources and labor.

Specific project objectives included:

- Validating the technology's ability to achieve FTP emission rates of approximately 2.5 g/bhp-hr NO_x with <0.05 g/bhp-hr PM, via engine dynamometer emission testing
- Determining any effects of the technology on engine performance, durability, and fuel efficiency
- Identifying and assessing in-service durability
- Assessing the impact of vehicle duty cycle on particulate filter regeneration performance

[4] During the course of this project, Acurex Environmental merged with its corporate parent, Geraghty and Miller, Inc., under the name ARCADIS Geraghty and Miller. ARCADIS Geraghty and Miller subsequently sold the Mountain View office of the former Acurex Environmental to Arthur D. Little, Inc., in January 2000. For the sake of simplicity, work by Acurex, ARCADIS, and Arthur D. Little is described collectively herein as having been performed by Arthur D. Little.

- Performing chassis-dynamometer emission testing to measure in-service emission rates
- Evaluating the cost impact of the technology, based on a compilation of fuel consumption and maintenance cost data
- Assessing the maturity of the technology and its commercial feasibility

3. Scope of Project Work

The project's scope of work consisted of the following five tasks:

- Task 1 — Host Fleet Identification
- Task 2 — Engine, Vehicle, and Particulate Filter Integration
- Task 3 — Field Testing
- Task 4 — Emissions Testing
- Task 5 — Data Analysis and Reporting

As the project progressed, a number of issues came up that were addressed by modifying the original scope of work. In some instances, like host fleet identification, additional work was needed since the original fleet choice did not meet the requirements of the contract. In other tasks, technology issues limited what could be achieved in the demonstration and, ultimately, led the project team to reduce the scope of the project.

The task descriptions below provide both the original scope and how it was modified based on the direction from SCAQMD and ARB.

Task 1 — Host Fleet Identification

This task included developing criteria for selecting the most suitable host fleet, contacting candidate fleets and soliciting their participation, and recommending a choice to SCAQMD and ARB staff. After a host fleet choice was approved by the client agencies, Arthur D. Little drafted a Memorandum of Understanding (MOU) with the host fleet to clearly set forth the responsibilities of the project manager and the host fleet. Host fleet selection criteria set forth in the Statement of Work included:

1. Having at least four vehicles equipped with Cummins B-series engines
2. Operating primarily in the South Coast Air Basin
3. Operating vehicles over duty cycles appropriate for this field test
4. Having a willingness to participate actively in the project

Suitable vehicle duty cycle characteristics included fairly high mileage accumulation rates (100 to 150 mi/day) and a mix of low-load and high-load modes. These characteristics would ideally uncover any durability issues, reveal any operating modes causing the particulate filter system to malfunction, and include sufficient high-load operation to properly regenerate the diesel particulate filter. In addition to these characteristics, we also wanted to test the technology in heavy-duty vehicle applications (gross vehicle weight rating [GVWR] >14,000 lb).

Task 2 — Engine, Vehicle, and Particulate Filter Integration

This task included integrating and demonstrating cooled EGR system, particulate filter, fuel-borne catalyst-dosing system, and associated control systems into the test vehicles. It also included performance dynamometer and road testing to demonstrate that the installed systems performed properly. Arthur D. Little subcontracted most of this work to Cummins Engine Company, and Rhodia Rare Earth's provided substantial assistance on the dosing system and trap system. Accordingly, this task included drafting a subcontract with Cummins Engine Company, and an MOU with Rhodia.

Task 3 — Field Testing

Field testing was originally planned to last 12 months and involved two vehicles equipped with the test engines and two similar control vehicles equipped with conventional Cummins B5.9 engines. Both the test vehicles and diesel controls were to be equipped with data loggers. The data loggers on the test vehicles were intended to capture diagnostic engine and exhaust system temperatures and pressures, duty cycle data (vehicle velocity [v(t)] and engine speed, [rpm(t)]), and operating time and mileage accumulation. This information was needed to determine the performance of the particulate traps. The data loggers on the control vehicles were intended to capture duty cycle data and mileage accumulation. Additional data on exhaust temperatures and pressures were not needed.

Additionally, manual data were recorded for daily mileage and fuel fills by host site personnel. Service on the vehicles performed by the host fleet, Cummins, or Rhodia was also planned to be recorded.

As the project proceeded, the scope of field-testing was reduced from two vehicles in the host fleet to one vehicle in the host fleet and one vehicle at Cummins. The length of the field demonstration was also cut short due to the time spent working on engine-filter issues.

Task 4 — Emissions Testing

The original statement of work called for performing both FTP (engine dynamometer) and chassis dynamometer emission tests. FTPs were to be performed on a newly built test engine/particulate filter system, and after the engine was removed at the end of field testing. Chassis dynamometer testing was to be performed on one of the test vehicles equipped with the test engine at approximately the same time as the FTPs.

The project team was particularly interested in determining the in-use emissions impact of the catalyst/diesel particulate system. A full set of chassis dynamometer emissions testing, encompassing regulated and unregulated emissions, was originally planned. Particulate chemistry and metal analyses were planned as well. Particulate size distribution was also later added to the list of characterizations needed.

Because of the particulate filter system malfunctions experienced during field testing, however, the scope of emissions testing was drastically reduced. The amended workplan called for performing the FTP on the first test engine/particulate filter system, prior to its installation in the test vehicle, and a comparison with certification emission rates of the current production-model Cummins ISB engine.

Task 5 — Data Analysis and Reporting

This task included monthly analysis and reporting of project results and data, progress meetings with the clients, and preparation of a final report at the end of the project.

4. Summary of Work Performed

This section summarizes the work performed on the project. As indicated in Sections 2 and 3, technical issues associated with the engine-filter system resulted in the project team substantially reducing the demonstration and emissions elements of the project. Nevertheless, substantial work was performed to develop a working system and field test this system for a limited period in-use. The work is described in the order of the tasks described in Section 3.

4.1 Host Fleet Selection

Initial project work focused on defining the characteristics of a suitable host fleet and test vehicle. The criteria that the project team agreed upon included:

- A fleet having a reasonably severe, high-mileage-service profile, with a mixture of starts, idling, and low-speed and high-speed operation
- A fleet having at least four mechanically similar vehicles, with similar routes and loads
- An operation in which vehicles returned to the same garage each day, rather than operating in intercity service
- A fleet employing heavy-duty vehicles (GVWR >14,500 lb)

Frequent starts and a high percentage of idling and low-speed operation were considered the most difficult modes from the standpoint of filter loading and regeneration. This follows from the fact that PM rates are high during starting and acceleration from standing starts. Approximately 30 minutes of uninterrupted high-load operation were needed to fully regenerate the loaded particulate filter, so the duty cycle had to include such a mode on a daily basis to achieve reliable filter regeneration. A true heavy-duty application was considered representative of the most likely actual market for a commercialized product. Four similar vehicles in similar service were needed for the planned test fleet of two test vehicles and two conventional diesel controls. A fleet operating out of a single garage was considered necessary in order for the project team to have reliable access to the fleet for data acquisition, equipment installation, servicing, and controlling fueling (early in the project it was not known whether an automatic dosing system would be available or manual dosing would be required either on board or at the fueling island).

Candidate fleets with whom Arthur D. Little project personnel discussed participation as host site included Cummins Cal Pacific (the Southern California Cummins dealer), Orange County Transportation Authority (OCTA), FedEx, and UPS. Cummins Cal Pacific's mechanics service mobile equipment in the field, using Dodge Ram 1-ton trucks with service bodies. Cummins recommended this application and Arthur D. Little secured Cummins Cal-Pacific's agreement to participate as host site, using the test engine installed in a mechanic's service truck. This fleet met many of the host site selection criteria. Several of Cal-Pacific's service trucks travel regularly to an open pit mine in Riverside. In this application the trucks were estimated to travel about 50,000 miles a year and had a combination of travel modes from surface streets to freeways and included traveling in and out of the open pit mine. The duty cycle was judged severe enough to test the system concept. This site also had the added advantage that the drivers would be trained Cummins mechanics that are interested in developing technologies and are also trained observers of diesel engine performance. It was felt that the Cal-Pacific drivers could play a more active role in the demonstration of the technology than normal fleet drivers.

The downside of this site was that the vehicles used were not heavy-duty applications. The Dodge service truck's GVWR is 10,000 lb and as previously stated the projected application for this technology was in heavy-duty uses (GVWR's >14,000 lb). SCAQMD and ARB directed the Arthur D. Little team to stop work until an alternative site and fleet could be identified. This stop work lasted four months as the Arthur D. Little team worked to contact possible sites meeting the host fleet selection criteria.

Seeking other potential host sites took longer than anticipated due to the constraints of finding a fleet that wanted to participate but also operated at least four vehicles over similar routes using the Cummins 5.9L diesel engine. Ultimately, Arthur D. Little secured UPS's agreement to participate as host site. UPS's package cars were suitable heavy-duty vehicles operating over appropriate, but demanding stop-and-go duty cycles, and had worked well with Cummins during previous Cummins field tests. Accordingly, the project team recommended that UPS be selected as the host site. An MOU defining the responsibilities of Arthur D. Little and UPS for the field test was drafted in September 1998. Following negotiations and revisions, the MOU was executed on April 5, 1999. During the September 1998 - March 1999 period, Arthur D. Little and UPS cooperated on the project on the assumption that the MOU would be finalized — the long process of reviewing and revising the MOU did not delay the progress of work.

The test fleet was based at UPS's San Bernardino depot, located at 1457 East Victoria Avenue, San Bernardino, CA 92408. It consisted of late-model UPS package cars, used for delivering parcel freight in San Bernardino and northern Riverside Counties. Figure 1 is a photograph of the UPS test vehicle. Essential vehicle data are shown in Table 1. Note that the control vehicle (No. 650605) was equipped with a mechanically-injected B5.9, while the test vehicle (No. 650604) was equipped with the newer electronically-injected ISB5.9 developed in this project.

The San Bernardino depot was chosen as the test site because package cars serving high-mileage routes to Big Bear Lake in the San Bernardino Mountains are based in San Bernardino. Package cars traveling to Big Bear from San Bernardino climb several thousand feet, at high speed, before making their first delivery stop, and accumulate 120 to 160 miles per day. Rhodia considered this to be a good route for testing engine and filter system durability, while providing sufficient daily high-load operation for effective filter regeneration.

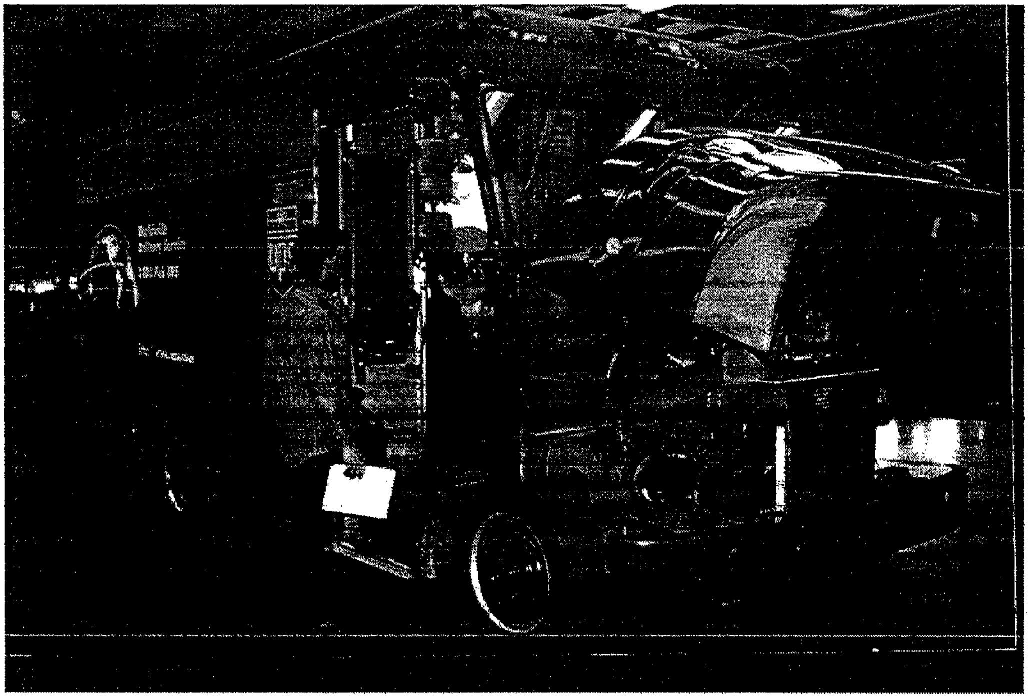

Figure 1. UPS Test Vehicle - Package Car No. 650604

Table 1. Characteristics of the Test Fleet

Datum	Test Vehicle	Control Vehicle
Vehicle model year	1996	1996
Chassis	Freightliner	Freightliner
Body manufacturer	Osh Kosh	Osh Kosh
VIN	40Z749E2452109162	—
GVWR	19,000	19,000
UPS vehicle No.	650604	650605
Engine serial No.	56432328	—
Engine model and year	Cummins ISB5.9 - 1998	Cummins B5.9 - 1996

Because of the unexpected need to do development work on several filter configurations during the course of field testing, limitations in available time and resources precluded installing a test engine and filter system in a second UPS package car. Cummins used a 1996 Dodge Ram 3500, based in Columbus, Indiana, as their test vehicle for filter system development. Cummins installed in this vehicle the second test engine system developed for this project. Cummins' Dodge Ram served, in effect, as the second test vehicle for the project. This truck was referred to by Cummins as the "Green Truck."

4.2 Engine, Vehicle, and Particulate Filter Integration

When the project was originally proposed the project team thought we would be able to integrate the engine and trap system at a Cummins dealership and then demonstrate the vehicles at the selected host site. This approach was more or less a field retrofit and it was judged by the project team at the beginning of the project to be too risky. The team recommended instead that Cummins perform the engine demonstration work at their Engineering Center in Columbus, Indiana so that the engine, filter, and vehicle systems could be better integrated. An added advantage of this approach was that the system developed would be integrated and, therefore, much closer to commercialization.

Table 2 outlines the work that Cummins was responsible for in this project. As indicated they were responsible for developing the cooled exhaust gas recirculation system for the 5.9L engine and for developing the EGR control system. Cummins worked closely with Rhodia on the specification of the filter system and its integration with the 5.9L EGR engine and UPS package car. Cummins was responsible for optimizing the engine to achieve emissions objectives and for providing emissions testing. Their scope also covered vehicle checkout testing and vehicle shipping.

Rhodia was responsible for the dosing and filter systems. Table 3 outlines their responsibilities. Rhodia was responsible for demonstrating the on-board cerium dosing system, installing the system on the vehicles, and calibrating the system to supply the needed concentration of cerium in diesel fuel. Rhodia was responsible for the filter system, and providing data loggers on the vehicles testing the filter technology. Finally, they agreed to provide technical support for the dosing and filter systems throughout the project.

The following sections describe the work performed by the project team to integrate, test, and demonstrate the EGR-filter system on the Cummins 5.9L engine and then on vehicles. Because of extensive troubleshooting necessitated by the malfunctioning filter systems, the project began to evolve from a demonstration project into a development project, though such development was outside the original scope and intent of the project. Multiple issues with filter plugging required the project team to investigate a variety of filter systems before a system was found to have some success. This caused delays in field testing and ultimately reduced demonstration time to a couple of months instead of the planned 12 months.

4.2.1 Technical Description of the Diesel Engine Technology Utilized

The performance goal for the test engines was to demonstrate FTP NO_x rates at or below 2.5 g/bhp-hr, along with PM rates below 0.05 g/bhp-hr. The catalyst technology demonstrated in this project is considered particularly suitable for achieving this goal with the Cummins B5.9. Considerations of cost versus performance have led this market segment to traditionally have in-line fuel injection pumps, high-pressure fuel lines, and injection nozzles, rather than the more expensive unit injectors found in heavy heavy-duty engines. In-line pumps typically develop injection pressures around 18,000 psi, while unit injectors develop pressures as high as 28,000 psi. Higher

Table 2. Work efforts performed by Cummins

Work Element	Description	Started	Completed
1	Purchase EGR control system hardware for two engines		X
2	Develop EGR control system and data links to engine controller		X
3	Purchase mechanical EGR hardware for two engines		X
4	Purchase two test platform ISB engines		X
5	Install EGR hardware and control system in engines		X
6	Install engines in vehicles		X[a,b]
7	Re-install original engines in vehicles at end of test		X
8	Ship vehicles		X[b]
9	Measure engine wear dimensions at beginning and end of test		X
10	Perform steady state engine mapping		X
11	Provide emission certification data for current technology engines		X
12	Conduct engine dynamometer emission tests at start and end of field test	X[c]	
13	Provide technical support during field testing	X	
14	Assist Arthur D. Little in data analysis and reporting	X	

[a] Test truck at Cummins ("Green Truck")
[b] First UPS vehicle
[c] Engine in UPS vehicle tested

Table 3. Responsibilities of Rhodia

Work Element	Description
1	Purchase cerium dosing system hardware for two vehicles
2	Perform dosing tank calibration
2.1	Purchase and package diesel particulate filter systems
2.2	Single Ibiden trap
2.3	Dual Ibiden traps with electric heaters
2.4	Cordierite low density trap
2.5	Metallic trap
3	Install dosing system and particulate traps in vehicles
4	Conduct validation testing on installed systems
5	Purchase data loggers and cellular modem systems
6	Install data loggers on test vehicles
7	Provide technical support for dosing and filter systems during field test

pressures improve fuel atomization and decrease ignition delay. These characteristics allow lower PM rates at a given NO_x rate with unit injectors, compared to in-line pump/line/nozzle systems. Therefore, engine manufacturers generally consider it more difficult to meet the MY 2004 NO_x and PM standards in a light-heavy-duty engine than in a heavy-heavy-duty engine. It is likely that heavy-heavy-duty engines will meet the MY 2004 NO_x standard (in October 2002 as per the consent decree) using a combination of EGR, variable geometry turbochargers, optimized calibrations, and exhaust aftertreatment by a simple oxidation catalyst.

Cummins considered fuel-borne catalyst regenerated particulate filters to be a potentially practical emission control technique for the B-series engine, and began testing EOLYS-catalyzed particulate filters before the present project began. Using a 3.0 L silicon carbide diesel particulate filter manufactured by Ibiden, Cummins demonstrated good regeneration performance over several thousand miles of field testing in a Dodge Ram 1-ton pickup truck, equipped with a 1996 B-series engine. This mechanically injected engine was not equipped with EGR.

The B5.9 engine was developed in the early 1980s, intended for on-highway vehicle applications in Class 4-7 (14,000 – 33,000 lb GVWR) trucks. In addition to trucks and buses, it is currently marketed in a variety of applications, including mobile construction and agricultural equipment, generator sets, pumps, and marine propulsion. It has the highest sales volumes of any Cummins engine model. According to the manufacturer's estimates, more than 1.7 million B-Series engines have been sold in these various markets.[5] The U.S. Environmental Protection Agency (EPA) and the ARB currently certify all automotive versions of the B-Series as a heavy-duty diesel engine (HDDE), with an intended service class designation of medium-heavy-duty diesel engine (MHDDE). This class has a useful life of 185,000 miles.[6] The engine is turbocharged and aftercooled, and is offered with horsepower ratings of between 175 and 250 bhp at approximately 400 ft-lb of torque.

The principal on-highway markets for the B-Series engine fall into three major segments:

- Class 4-7 trucks
- Medium-sized transit and shuttle buses between 25 and 30 feet in length, with GVWRs of between 20,000 and 30,000 lb
- Medium-duty Dodge Ram pickup trucks

[5] "Big Changes for Cummins' B Series," *Diesel Progress, North American Edition,* May 1997, p. 14.

[6] *1996 LARGE ENGINE EPA CERTIFICATION SUMMARY REPORT,* published on the EPA World Wide Web site at www.epa.gov/omswww.

Approximately 700 to 800 B-Series engines are sold in Class 4-7 trucks per year in the South Coast Air Basin.[7] Freightliner's FL 50, FL 60 and FL 70 "Business Class" trucks are popular chassis in this class in which the B-Series is the most popular engine.

The B5.9 is by far the most popular engine in the medium-sized transit bus market. El Dorado National and Blue Bird are two of the largest U.S. manufacturers of these vehicles. The Cummins B5.9 is the only engine used in El Dorado's 25-ft Escort model, and the primary engine offered in their larger (30-ft) Transmark. Blue Bird's Transhuttle (25,700 lb GVWR) is also exclusively powered by the B5.9.

The test engine was based on the new Interact System B-Series (ISB) engine, which Cummins began offering commercially in MY 1998. Previous B-Series engines were mechanically injected and governed, and were aspirated through single intake and exhaust valves per cylinder. Gas flow through the combustion chamber was longitudinal, as the intake and exhaust manifolds were located on the same side of the engine. The ISB incorporates an advanced electronic injection control system, and a redesigned head that features four valves per cylinder and a centrally located fuel injector. The ISB head is a cross flow design, with the intake and exhaust manifolds located on opposite sides of the engine. The new head configuration yields a substantial reduction in intake flow resistance, and improved combustion characteristics. The test engine used a production ISB engine control module using a non-production low-NO_x calibration.

4.2.2 Cooled EGR System

Production ISB engines certified to California's medium-duty vehicle standards are equipped with uncooled EGR to reduce NO_x. Uncooled EGR gas temperatures can be as high as 650 to 700°F, depending on engine load. If the EGR stream is cooled, peak firing temperatures are reduced more than with uncooled EGR, resulting in potentially greater NO_x reductions. The test engines for this project were equipped with an experimental cooled EGR system. In this system, exhaust gas flowing to the EGR valve is first cooled to a maximum of 300°F in a heat exchanger, using engine coolant (Figure 2). Cummins fabricated an exhaust manifold equipped with a port for bleeding off the EGR stream (Figure 3). The EGR stream was then fed to the heat exchanger mounted directly above the exhaust manifold (Figure 4). The EGR valve was vacuum-actuated, with vacuum controlled by a solenoid valve. The vacuum was provided by an electrically driven (12VDC) diaphragm pump that Cummins installed underneath the dashboard, above the engine doghouse (Figure 5). The vacuum pump was connected to a 52 in^3 vacuum tank, which provided a vacuum reservoir. The vacuum reservoir provided faster EGR valve actuation than was possible with the pump alone, and reduced the frequency at which the pump cycled on and off. Note that EGR rate was not modulated. The valve was either shut or fully open. With the EGR valve open, exhaust gas flowed through a crossover tube from the exhaust (right) side of the engine,

[7] Bob Kraft, President, Cummins Cal-Pacific, Inc., personal communication, October 1997.

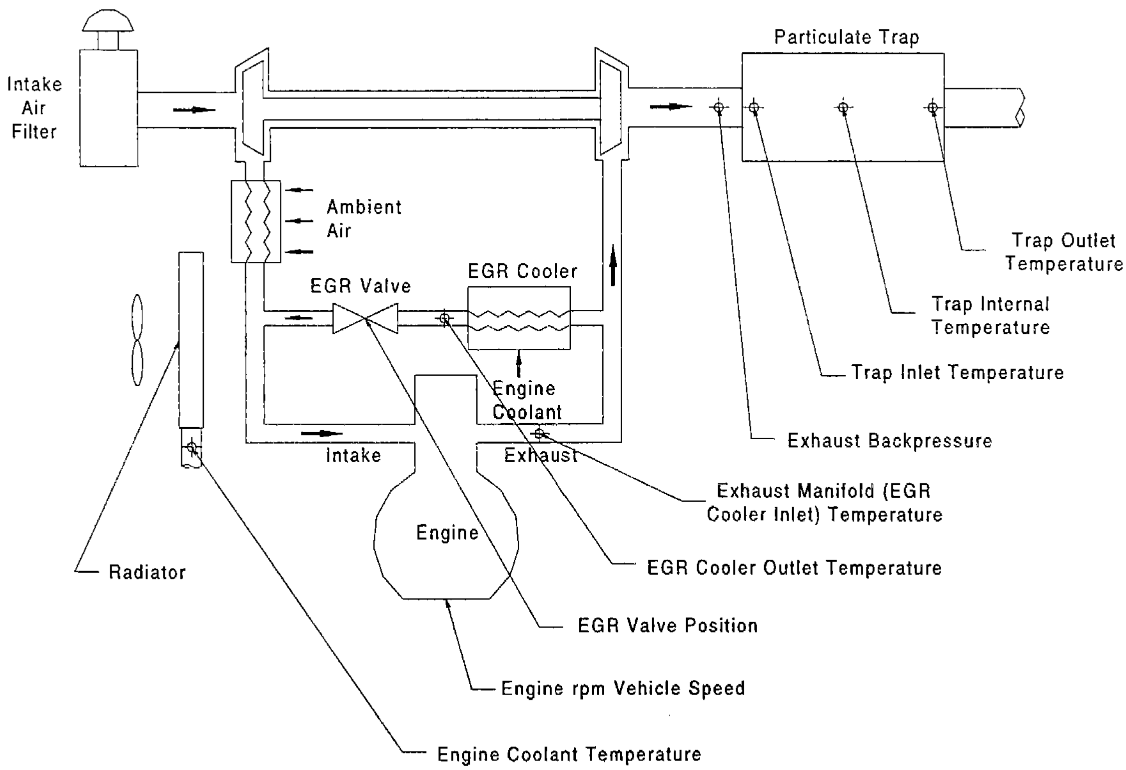

Figure 2. Test Engine Schematic and Data Logger Sensor Locations

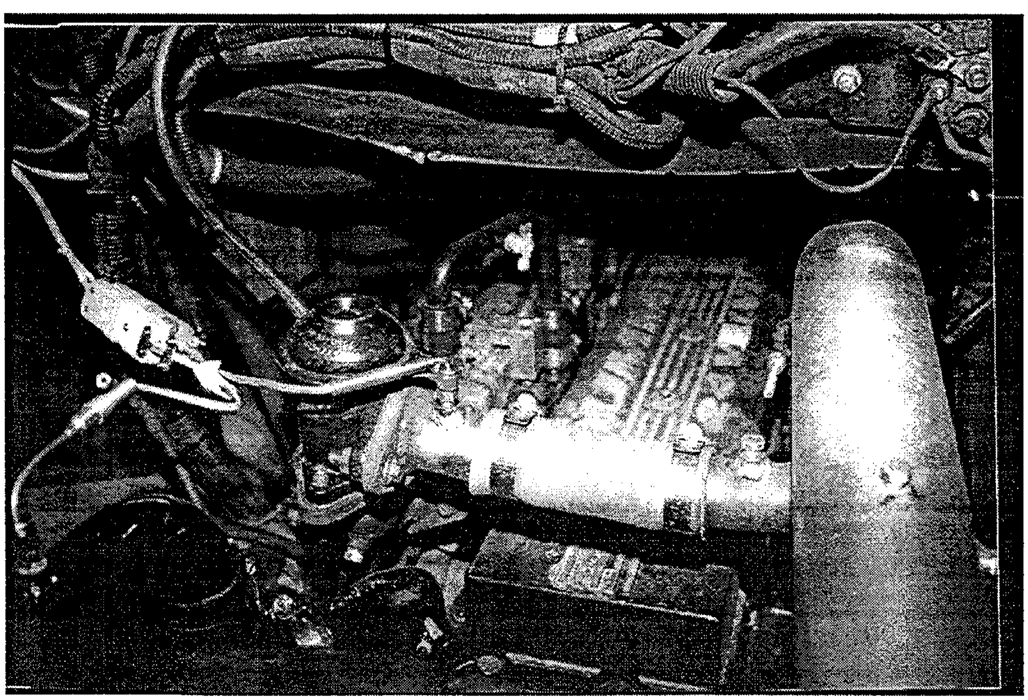

Figure 3. EGR Valve and Line Routing Exhaust Gas to the Intake Air Duct

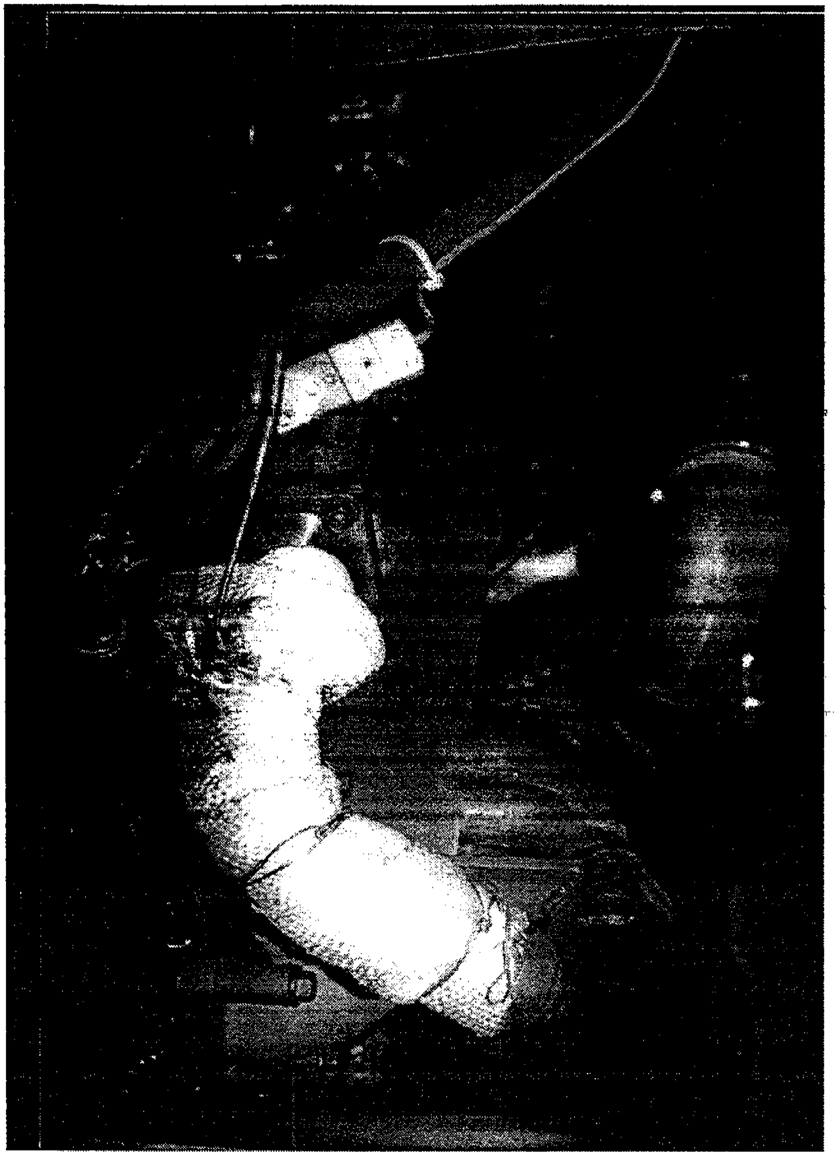

Figure 4. Inlet Side of EGR Cooler

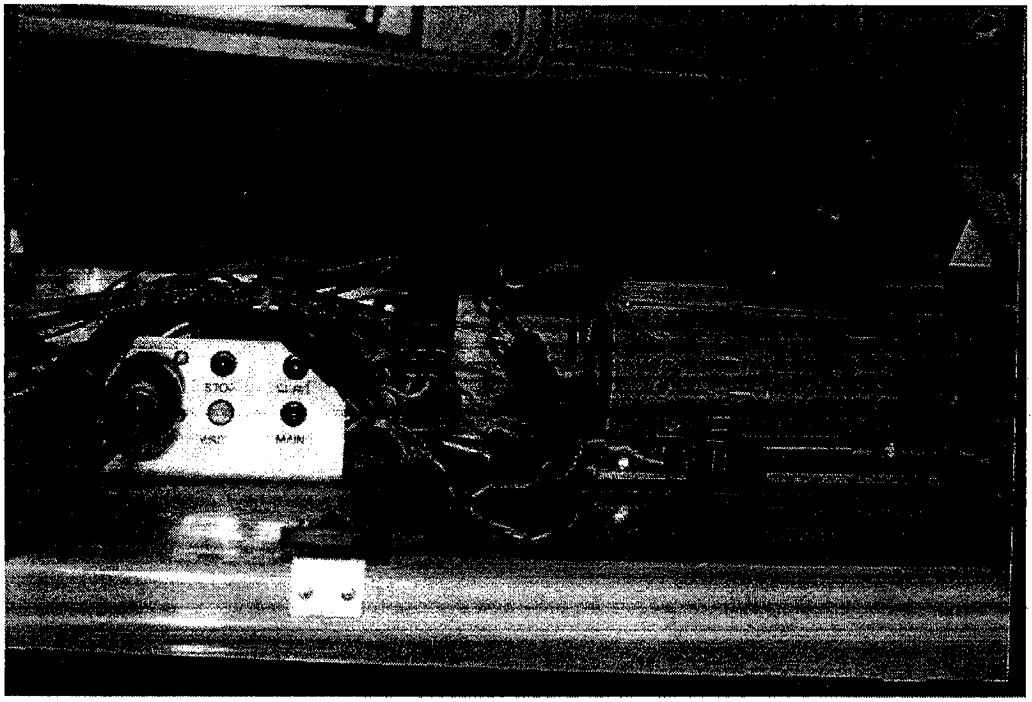

Figure 5. Vacuum Pump Used to Actuate the EGR Valve

into the intake manifold. Because the EGR gas was tapped from the exhaust manifold, EGR rate is a function of the difference in pressure between the exhaust manifold and the intake manifold; a higher exhaust pressure, relative to intake pressure, increases the EGR rate. EGR valve position was controlled by a programmable controller housed in a shock-resistant container bolted to a shelf in the cargo area (Figure 6). Optimizing EGR control was an important aspect of the system development effort for this engine. The EGR controller used inputs from the engine control module to monitor engine load and RPM. EGR is undesirable at idle and low loads, where it adversely affects driveability and causes power loss at full load. In the test engine, Cummins' calibration engineer was able to tailor the EGR control function to open the EGR valve during high particulate loads, where it effectively reduces NO_x formation without adversely affecting engine performance. The output of the EGR controller was either a 0V signal (EGR off), or 12V (EGR on) to the EGR vacuum valve.

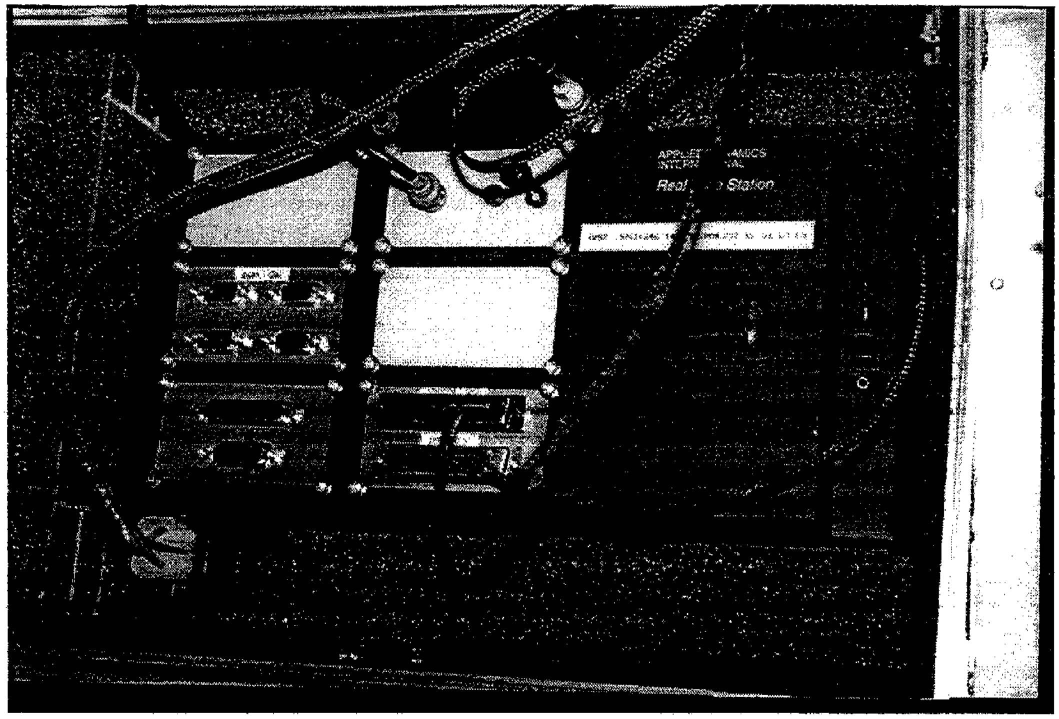

Figure 6. EGR Controller in its Padded Enclosure

4.2.3 Fuel-Borne Catalyst Dosing System

As indicated in Table 3, Rhodia was responsible for the dosing system. Two options were explored: island dosing and on-board dosing. Adding cerium at the fuel island would have been the easiest system to implement, but then there are always concerns about whether the drivers or servicers had used the correct fueling nozzle. Rhodia with agreement from the rest of the project team agreed to develop the more difficult on-board system.

Rhodia worked with Walbro Corporation to develop a system that would determine the amount of diesel fuel added to the vehicle fuel tank and then determine the amount of cerium to be added to the diesel fuel. The system was meant to be automatic with no driver or servicer interaction. The system would work for any amount of diesel fuel added to the vehicle. Walbro's approach was to develop a dispensing system that would dispense a higher concentration of cerium into diesel fuel. The system used a metering pump that was calibrated for dispensing a quantity of the higher concentration cerium per each stroke of the pump. The amount needed was determined from level measurements in the diesel fuel tank. A controller determined the amount of diesel fuel added and the amount of cerium needed. The controller sent a signal to the metering pump on the number of strokes needed.

This system was installed in the test vehicle with an instrument panel pump stroke counter and an LED signifying pump operation. The LED flashes for each pump stroke and illuminates continuously for a system fault or depletion of cerium to approximately 90 percent point. Pump stroking rate is about 54.4 strokes per gallon of diesel. For a complete vehicle refuel (32 gallons of diesel), it takes 29 minutes to complete the dispensing of cerium. Walbro also included features to add cerium only if the vehicle is moving to avoid possible confusion if the vehicle is parked on a grade. Faster dispensing was also a planned improvement.

The test vehicle was equipped with this automatic dosing system. The cerium fuel-borne or EOLYS catalyst was stored in a sealed steel tank that held 0.250L of the EOLYS product. This was sufficient to dose all of the diesel fuel consumed during the planned year of field testing. A metering pump and controller, supplied by Walbro Corporation was installed in the dosing tank. The pump controller monitored the fuel tank level, based on signals from the fuel tank's float gauge. Following a fuel fill, the controller estimated the fill volume from the increase in tank level, and directed the dosing pump to meter sufficient EOLYS solution to maintain a cerium concentration in the fuel of 50 ppm (weight).

4.2.4 On-board Data Logger

The test vehicle was equipped with automatic data loggers that recorded sensor outputs, as shown in Figure 7. A list of parameters recorded by the data logger is shown in Table 4. With the engine turned on, the data logger recorded all sensor outputs at 1.0-second intervals. The data were recorded for three purposes: (1) to document vehicle activity, as mileage accumulation can be estimated from the speed-versus-time data; (2) to define the vehicle's duty cycle; and (3) to record data useful for diagnosing the performance of the engine-trap system, and for troubleshooting failures.

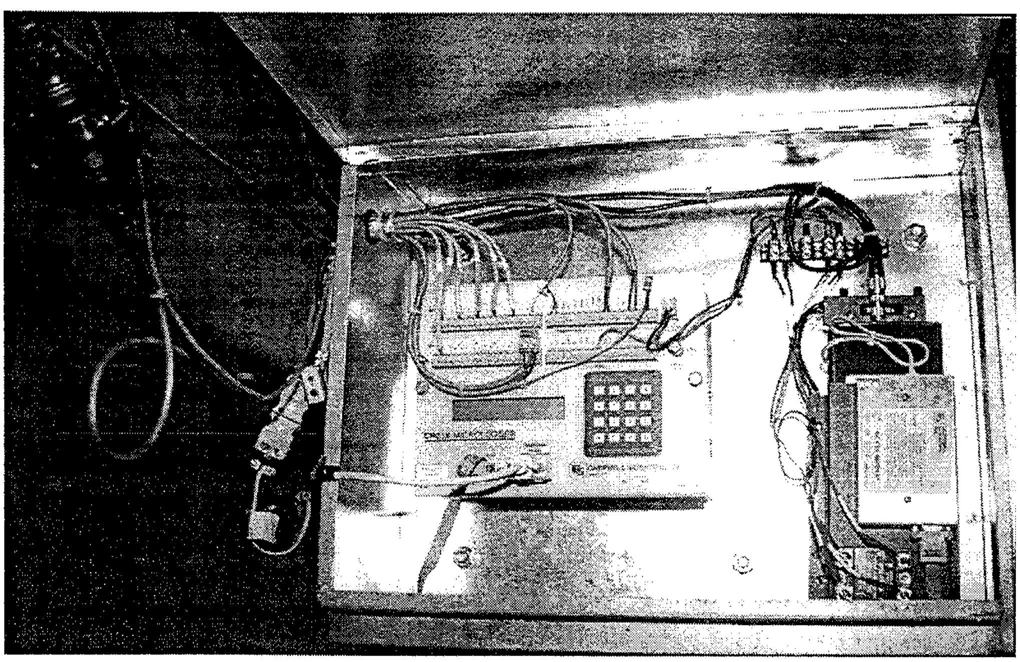

Figure 7. Data Logger and Cellular Modem Installed in the UPS Test Vehicle

Table 4. Parameters Recorded by the On-Board Data Logger

Parameter	Unit	Notes
Array ID number	(none)	ID number of data logger
Vehicle ID number	(none)	Last three digits of UPS fleet No.
Julian date	(none)	1 = January 1 365 = December 31
Time of day	hr:min	00:00 is midnight
Time elapsed during current minute	seconds	
Exhaust manifold pressure	[kPa]	Gauge pressure
Temperature at filter inlet	°C	
Temperature at filter center	°C	
Temperature at filter outlet	°C	
Engine speed	RPM	
Vehicle speed	mi/hr	
Fuel level – signal from fuel tank float gauge	Volt	Range empty-full = 3-8V
Cumulative dosing pump delivery	no. of strokes	
EGR cooler outlet temperature	°C	
EGR cooler inlet temperature	°C	
EGR controller output	Volt	0-0.3V: valve closed 13V: valve open
Engine coolant temperature at radiator inlet	°C	

The data loggers were specified and installed by Southwest Research Institute (SwRI), which performed the work for Rhodia. Equipment and installation costs were borne by Rhodia, as project cost share. The data loggers were equipped to download data through either a serial port or a cellular modem. The cellular modem allowed project personnel to phone the data logger and have it download data to a remote computer while the vehicle was in service or parked in the garage. This allowed project personnel to download operating data without having to travel to the host site.

4.2.5 Engine Calibration, Installation in UPS vehicle, and Performance Testing

The engine, EGR controller, and single-canister silicon carbide particulate filter system were assembled on a test stand and subjected to extensive steady-state performance testing. This was followed by emission testing, using the heavy-duty FTP, to verify that the project's emission and performance targets had been met. FTP testing verified that the engine achieved a NO_x rate of 2.53 g/bhp-hr and a PM rate of less than 0.03 g/bhp-hr, while developing rated power and torque (175 bhp at 2,500 rpm and 420 ft lb at 1,600 rpm). Emission test results are presented in more detail in Section 4.5.

Installation and initial testing of the engine/filter system were performed at Cummins Engineering Center in Columbus, Indiana. The UPS vehicle was picked up on July 27, 1998 and transported via flatbed truck to Columbus. The engine installation involved replacing the original mechanical throttle linkage with a potentiometer linkage suitable for the new electronically controlled engine. During teardown, Cummins mechanics discovered that the clutch was worn out (at only 27,000 miles since the last clutch replacement), and replaced it. The front brakes and tie rod ends were also repaired. The UPS package car was clearly subjected to severe service. Cummins removed the fuel tank and sent it to Walbro Corporation. Walbro personnel measured the tank to develop a function of tank volume versus tank level indicated by the float gauge, and packaged and calibrated the on-board tank and dosing system for the EOLYS fuel-borne catalyst.

As the test engine had a higher rating than the original engine (175 versus 160 bhp), and the EGR cooler would also increase heat rejection to the cooling system, Cummins performed extensive chassis testing to verify that the existing radiator would perform adequately with the test engine.

This involved exercising the engine on a chassis dynamometer to measure engine coolant temperature at various loads. With the test engine, coolant temperatures initially exceeded Cummins' specification at high loads. To resolve this, Cummins installed an aluminum duct between the hood and the perimeter of the radiator inlet, which increased the flow of cooling air through the radiator. Additional dynamometer testing confirmed that this modification produced adequate cooling at high load.

4.2.6 Diesel Particulate Filter Systems

The original work plan called for installing a single 3L monolithic particulate filter in place of the vehicle's muffler. A silicon carbide particulate filter manufactured by Ibiden was selected for this demonstration, based on previous successful experience in Japan and Europe with naturally aspirated diesel engines using cerium as a fuel additive. This filter was chosen over other candidate designs for several reasons. First was durability. Silicon carbide can withstand thermal and vibrational loads better than the cordierite material use in most particulate filters. Second was thermal resistance of the filter material as soot accumulation was expected during the driving cycle. It is now well known that cordierite is unable to sustain high soot loading without melting problems (runaway regeneration) during the subsequent regeneration. Third, the silicon carbide Ibiden filter featured lower weight and faster warm-up than cordierite filters. And, fourth was the small size. Ibiden selected the cell density and capacity for this filter at 300 cells/in^2 and 3.3L (6.5-in diameter by 6-in length).

This filter was installed in the first of the two planned UPS test vehicles at Cummins Technical Center and then was subjected to test driving. During test driving, the particulate filter exhibited an immediate, severe increase in backpressure. Inspection of the filter revealed severe coking at its face. Cummins and Rhodia personnel attributed this phenomenon to a feedback mechanism between the filter and the EGR system. Unburned fuel present in the exhaust during starts apparently deposited on the filter face, restricting flow area and increasing the filter's backpressure. This increased the exhaust manifold pressure, which, in turn, increased the EGR rate. Excessive EGR rates caused poor combustion, which produced more unburned fuel that deposited on the filter face. This behavior was self-reinforcing, and led to rapid plugging of the filter at its face.

The project team's efforts to solve the filter plugging problem led to three additional diesel particulate filter configurations being installed and tested:

1. An electrically heated dual filter system, using twin 6L Ibiden monolithic silicon carbide filters having a cell density of 300 cells/in^2 (CPSI)
2. Cordierite 100 CPSI (6.5L) – installed in Cummins Dodge Ram test truck ("Green Truck")
3. Metallic 19L installed in Green Truck and in the UPS package car

Details of the design and performance of these filter systems are discussed below.

ISB Engine with Cooled EGR and Unheated Ibiden Silicon Carbide Particulate Filter
In early October 1999, Cummins completed installation of the engine-filter system in the UPS package car, and began road testing in Columbus, Indiana. While the filter system performed well in the absence of EGR, activating the EGR system led to a rapid and severe increase in filter backpressure. Data recorded during the event showed exhaust manifold pressure increasing from approximately 18 in. Hg to over 50 in. Hg (see Figure 8). Inspection of the filter element showed that its face was plugged with soot and pyrolized fuel residue. The likely cause of the problem appeared to be an interaction between the filter and EGR systems: unburned fuel emitted during starts accumulated on the filter face and pyrolized. This created a flow restriction in the filter face, which increased the pressure in the exhaust manifold. The increased pressure difference between the exhaust and intake manifolds led to an increased EGR rate, which, in turn, caused deterioration in combustion quality. More unburned fuel was then deposited on the filter face, increasing its flow restriction and further increasing the EGR rate. This feedback loop led to rapid face plugging.

As a result of this face plugging on the Ibiden filter, the project team recommended that the filter system be removed and the UPS truck shipped back to California and put back into service. The project team needed time to assess the filter plugging problem and to develop hardware solutions. The team did not want to inconvenience UPS during this period and also wanted to obtain data on the truck operating with the EGR system to see whether any in-use issues would arise with this system.

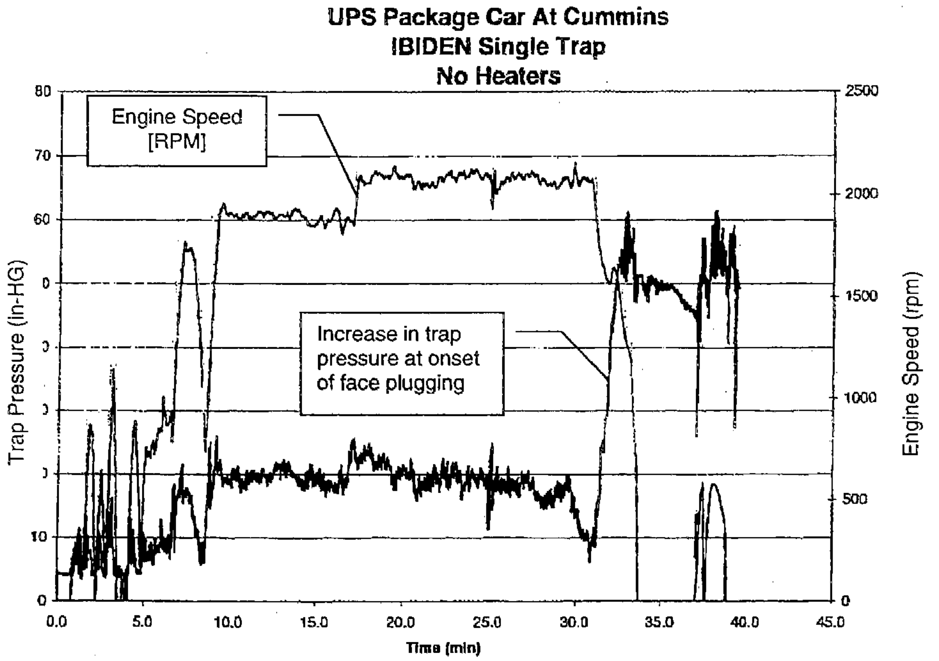

Figure 8. Increase in Exhaust Pressure During Plugging of the Unheated Silicon Carbide Filter

Twin Electrically-Heated Ibiden Silicon Carbide Particulate Filter System

After reviewing the filter face plugging in detail, Cummins and Rhodia concluded that filter plugging was caused by soot buildup on the face of the filter. They felt this mechanism could be solved by using electric face heaters that could force regeneration if the face began to plug. At that time, Rhodia was demonstrating electrically heated particulate filters in a diesel delivery truck in Mexico City. The truck was powered by a Mercedes-Benz medium-heavy-duty engine. Regeneration performance of the electrically heated particulate filter in this application was excellent. The bottled beverage delivery truck operated with frequent stops and starts, similar to the service of the UPS package car. The Mercedes engine was not equipped with EGR, however, so the impact of EGR on particulate filter performance could not be inferred from the Mexican field test. Nevertheless, the electrically heated particulate filter appeared robust enough to work in the UPS application. It would allow the vehicle to remain operational while generating field test data to better understand the filter plugging mechanism and investigate techniques to reliably prevent plugging; the viability of the fuel-borne catalyst concept still depended on demonstrating its ability to reliably initiate filter regeneration without external heat.

Exhaust gas flowing through a particulate filter while an electric face heater is operating absorbs the heat and tends to limit the temperature rise of the gas severely enough to prevent regeneration. Unless extremely high heating power is available, electric heating is only effective if the exhaust flowrate is kept quite low. In practice, this requires that two filters be operated in parallel. This allows the exhaust flow through the filter undergoing regeneration to be restricted, while the other filter remains operational. Butterfly valves are typically used to restrict exhaust flow during regeneration. Pressure transducers and an electronic controller are needed to detect the onset of filter plugging and initiate regeneration. Several months were needed to design, build and test the proposed electrically heated filter system. For testing purposes, Cummins installed an ISB engine with cooled EGR in the Green Truck, and test drove it extensively with the electrically heated filter system and cerium manually added to the fuel tank. The system performed well in the Green Truck.

A schematic of the dual-filter system is shown in Figure 9. It included two filters, valving to control which filter is collecting or regenerating, and an electronic controller. Using a pressure transducer installed just upstream of the particulate filters, the electronic controller monitored exhaust pressure, and determined if exhaust pressures had become excessive due to filter loading. If it determined that the operating filter was loaded, the controller opened the butterfly valve to the opposite filter, closed the loaded filter, and began heating it. Each electric heater consumed 1,400 W while it was switched on. With a 12V electrical system, this requires a current of 116 A, necessitating the installation of a higher-output alternator in the UPS package car. Vacuum was needed to actuate the butterfly valves. The existing vacuum system for the EGR valve was used to supply vacuum for actuating the butterfly valves in the particulate filters. The controller controlled vacuum actuation through a pair of solenoid valves. In addition to the exhaust lines flowing to the two electrically-heated particulate filters, the UPS car's exhaust system was equipped with a bypass pipe, normally

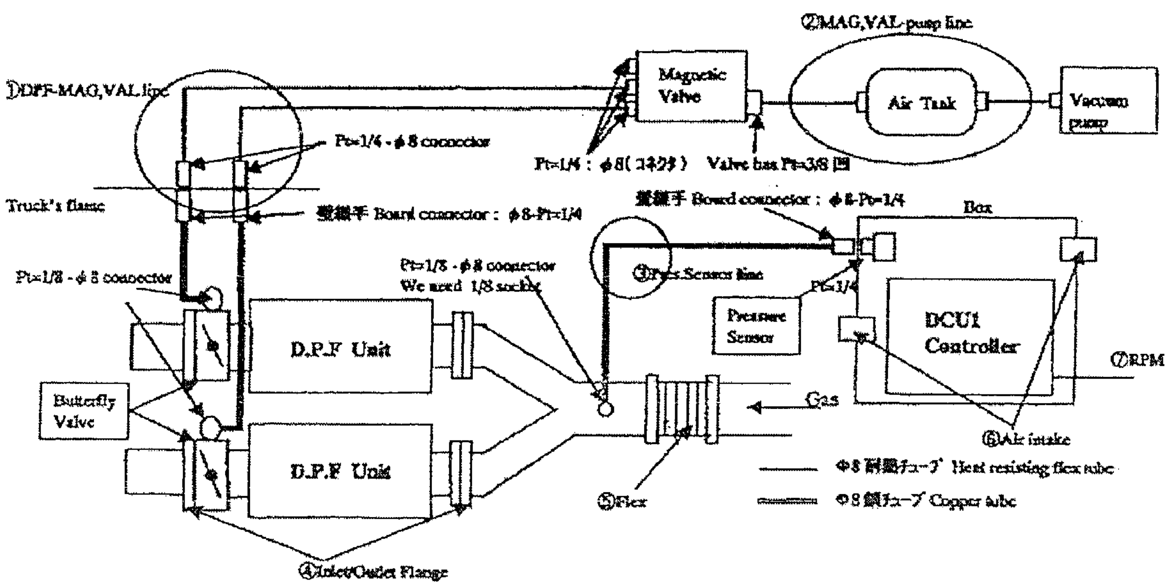

Figure 9. Schematic of the Electrically Heated Particulate Filter System

blocked with a plug valve. In the event of filter plugging, the bypass pipe could be manually opened to allow the vehicle to continue operating. Figure 10 shows the front of the electrically heated filter system on the UPS test vehicle, and Figure 11 shows the rear. This system was far more complicated than the originally installed single filter and fuel-borne catalyst system. However, based on the experience with the first filter design, the project team considered it prudent to install an overdesigned system to prevent filter plugging in service. In addition, with this system it was possible to disconnect components and possibly simplify the system as field experience was obtained.

After the system was installed in the UPS package car, it was tested in normal service on February 19, 1999 (results are also described in Section 4.3.4). The vehicle performed well during the climb from the San Bernardino depot to Big Bear. High exhaust temperatures were recorded on the climb to Big Bear and pressure drop date indicated that regeneration took place. However, the vehicle started to behave poorly soon after several delivery stops. The engine ran rough with reduced power. Cummins and Ibiden personnel evaluated system and concluded that face plugging had again occurred.

Face plugging was a surprise since this failure mechanism had not been observed in testing the system on the Green Truck (which had the same system installed.) Further analyses of the data indicated that the UPS duty cycle included a substantial number of engine starts during the driver's route. Figure 12 illustrates that this route has some 70 engine off events lasting one or two minutes to almost 25 minutes for the driver's lunch. UPS practice is for the drivers to turn off the engine and remove the key at each delivery stop.

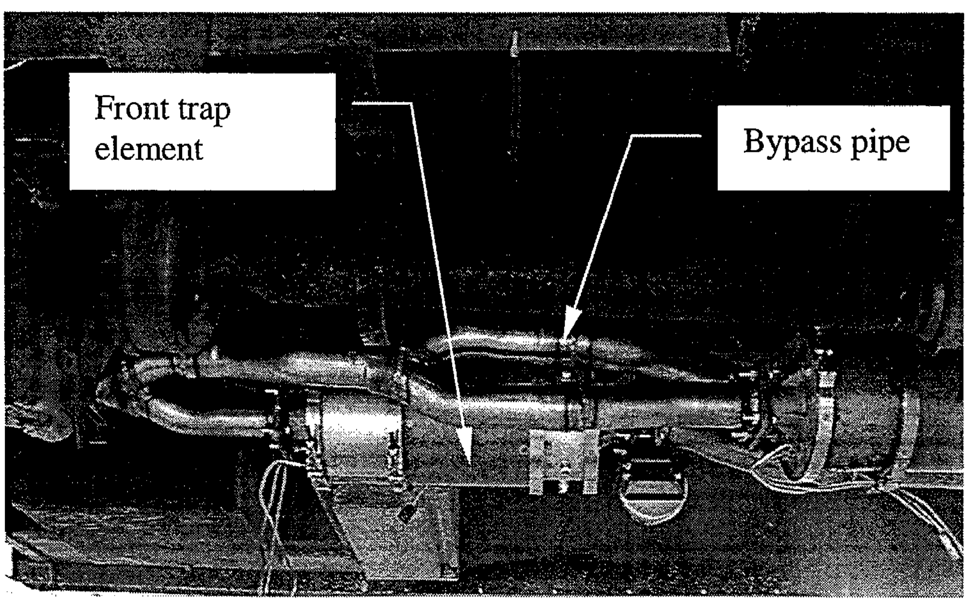

Figure 10. Electrically Heated Particulate Filter System, Showing Front Filter Element and Partial View of Rear Element

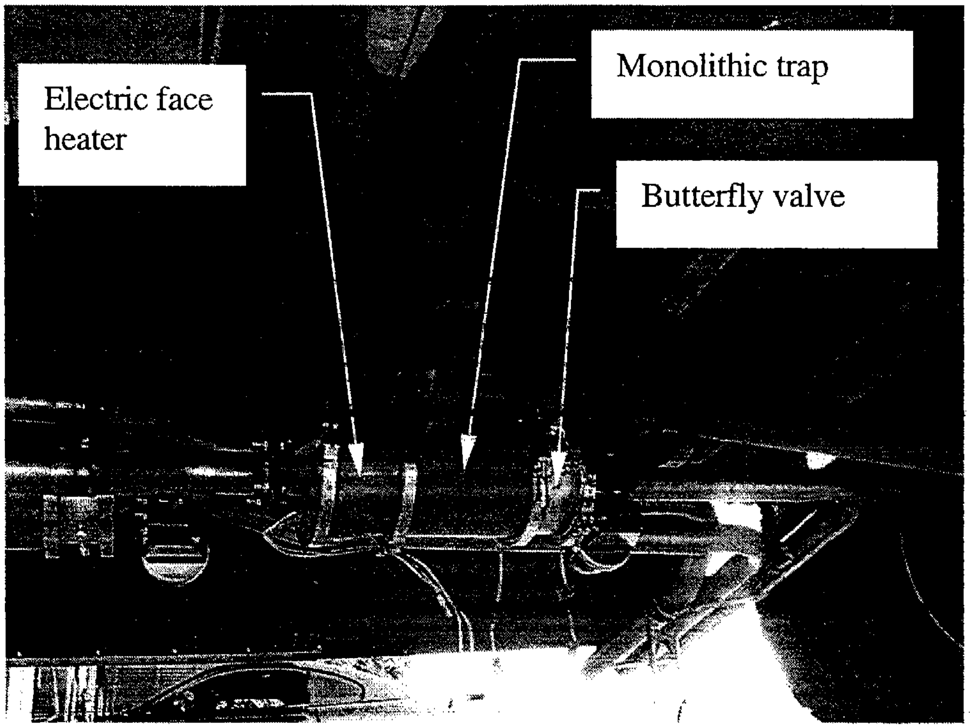

Figure 11. Rear Electrically Heated Filter Element

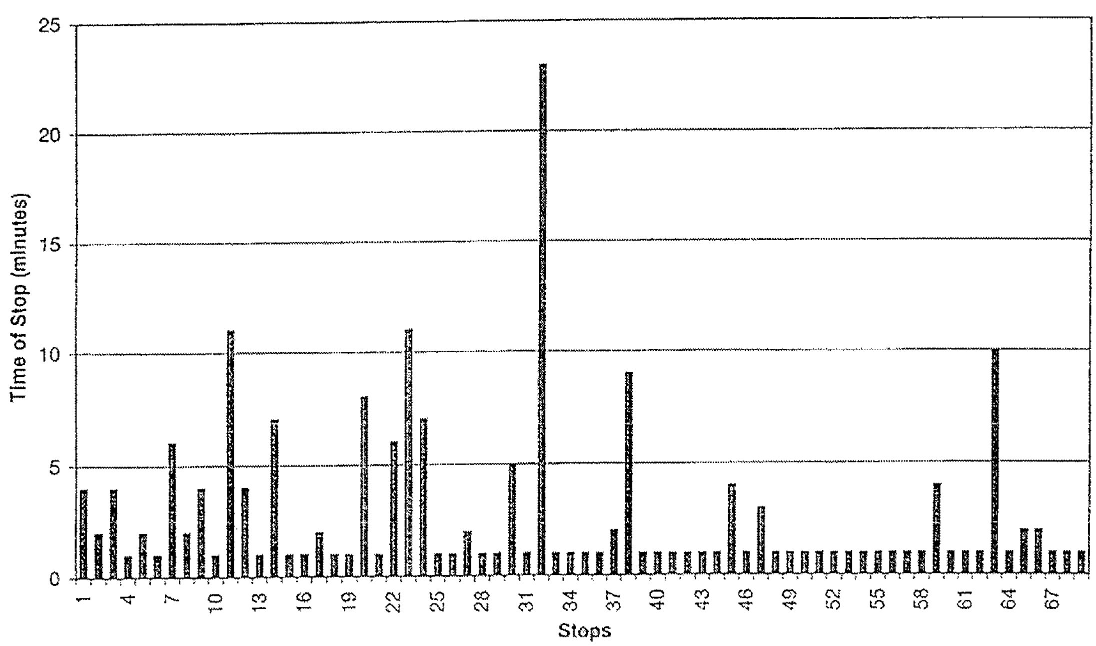

Figure 12. Number and Duration of Engine Stops on UPS Route

This type of duty cycle was not simulated in any of the vehicle checkout testing at Cummins. The significance of these restarts is that during each event the engine is slightly overfueled to start. It was speculated that unburned fuel was depositing on the face of the filter and later coking as the exhaust temperature increased (or as the heater element was initiated). If this hypothesis was correct, a possible solution could be to reduce the cell density of the filter. It was also later determined that the on-vehicle dosing system was not operating and no cerium was being added to the fuel (see discussion in Section 4.3.4). The rapid build up of backpressure after a few engine restarts indicated that face plugging was the primary problem and not plugging of the filter itself. Cerium is effective at lowering the temperature for regeneration in the filter, but as was proven by subsequent testing not in solving filter face plugging.

Third System – 6.5L Cordierite w/100 cells/in^2 Density — Tested in Cummins Green Truck

In March 1999, Cummins installed a new filter system in their Green Truck for evaluation. This was a cordierite wall flow monolith, manufactured by Corning. It had a cell density of 100 cells/in^2, and was catalyzed with a platinum washcoat – It did not employ the EOLYS fuel-borne catalyst. This filter was installed to evaluate the effectiveness of a lower cell density for preventing face plugging (recall that the cell density of the Ibiden silicon carbide filters was 300 cells/in^2), and the potential of the catalyzed washcoat for stimulating regeneration, in lieu of the fuel borne catalyst. Cummins road tested the system by operating the Green Truck around the Columbus, Indiana area. In late March 1999, Cummins reported that this filter plugged after less than 1,000 miles of operation. Inspection of the filter showed that face plugging had *not* occurred; rather, soot had built up along the length of the cells, and the filter had failed to regenerate. This test indicated that a lower cell density could eliminate face plugging, but that the highly loaded platinum washcoat was unable to initiate regeneration.

Fourth System — Metallic Catalyst

The fourth and last particulate filter system tested in the project was a metallic substrate parallel plate design. This was a filter (although cell density is not appropriate with this system. it is estimated that this filter would be similar to one with a cell density of 100 cells/in^2), manufactured by HJS of Germany. Rhodia had successfully tested this filter design in a diesel postal delivery vehicle and a package delivery vehicle. Both of these vehicles had frequent starts like the UPS test vehicle. In the HJS filter, each cell is enlarged at the face (see Figure 13). It was hypothesized that this geometry would inhibit face plugging. With the large frontal flow area of this filter, and using the EOLYS fuel-borne catalyst at a concentration of 50 ppm cerium, the project team hoped to avoid both face plugging, and the wall plugging exhibited by the third filter system. While the metal filter could withstand high thermal and soot loading, it had a higher thermal mass than the silicon carbide filters used previously. The project team was concerned that this might cause smoke to appear during starts, due to condensation of hydrocarbon and water in the filter. In addition, the only filter that was available from HJS was very large at 19L. The intent was to test this filter concept to see if the filter solved face plugging and would regenerate using cerium.

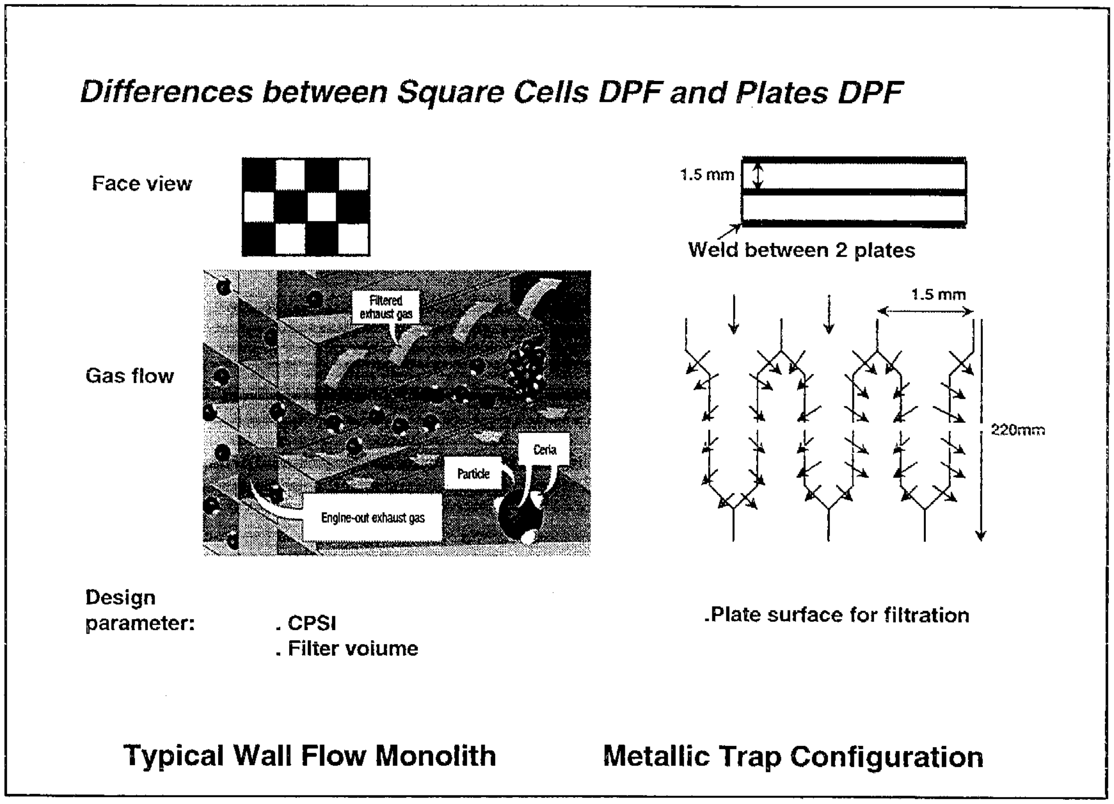

Figure 13. Metallic Filter Wall Geometry

In April 1999, Cummins installed the HJS filter in the Green Truck, and began test driving in the Columbus, Indiana, area. EOLYS was manually added to the diesel fuel tank to maintain the desired concentration of 50-ppm cerium. The Green Truck was initially operated over 5,000 miles of suburban and rural highway driving, with approximately 5 starts per day. No face plugging or wall plugging occurred. Data logger records indicated that the filter was regenerating properly.

Following this success, Cummins performed two days of testing to simulate the UPS driving cycle. This involved running at low speed, stopping and shutting down the engine for a few minutes, then restarting. The truck was operated through 50 starts on the first day, and then 100 starts on the second day. During all of this testing, the filter regenerated as expected. The pressure drop across the filter remained quite low, never exceeding 2 in. Hg. After regeneration, the pressure drop consistently returned to 1 in. Hg. Also, cold-start emissions did not appear to be significant. Little or no white smoke was generated.

Cummins then increased the severity of filter loading by modifying the EGR control to keep EGR on at all times, even during full-load acceleration. This operating mode led to increased filter loading when the exhaust temperature remained below 325°C.

Increasing the exhaust temperature to above 400°C for a minimum of 1 minute caused the filter to fully regenerate. Figure 14 illustrates filter regeneration after about 200 stop-and-go's at about 42 minutes of on highway, loaded conditions where temperature exceeded 350°C.

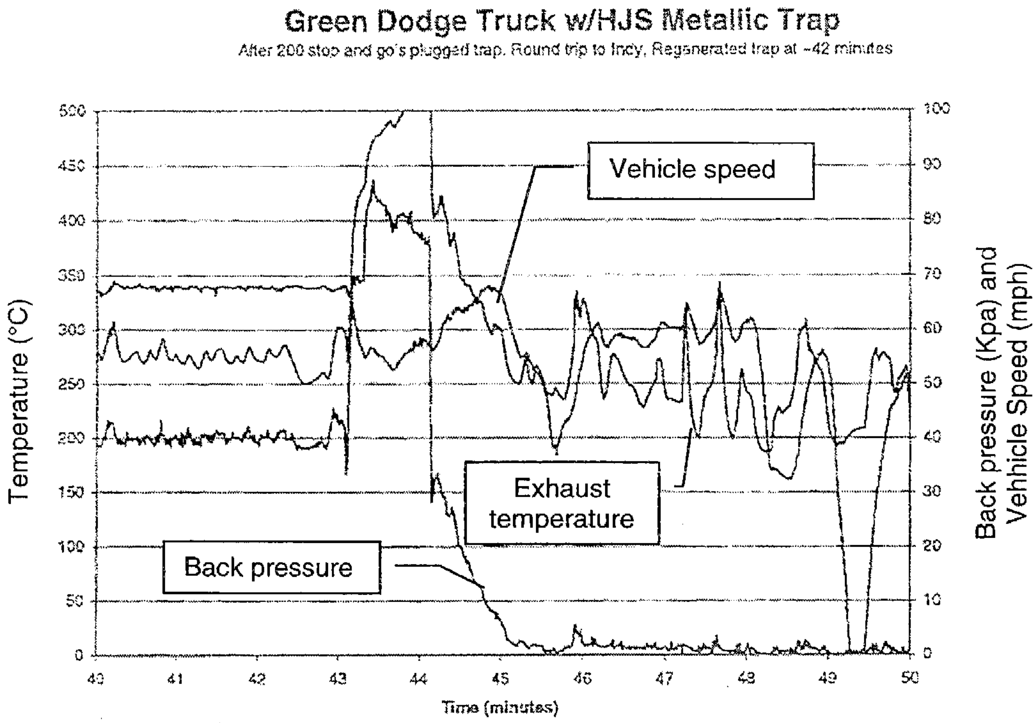

Figure 14. Successful Metallic Trap Regeneration After 200 Stops and Starts

Based on the success of this testing, the project team recommended installing the HJS system in the UPS vehicle. This was done and demonstrated for a limited time as indicated in Section 4.3.3.

Summary of Issues with Filter Systems

The Green Truck testing work at Cummins proved invaluable for troubleshooting the issue of filter face plugging. Cummins repowered this truck with the second EGR engine and filter systems to determine a solution to face plugging. Although there was a lot of experience with the Ibiden system, this experience was on smaller displacement engines without EGR. In fact, the project team thought that face plugging was a result of EGR causing increased sooting. The solution, therefore, was to use a system that would burn off the soot at the face of the trap.

It was not until the UPS duty cycle was better understood that the mechanism of face plugging was associated with the number of engine restarts. The single Ibiden filter system failed because of face plugging most likely caused by unburned fuel during restarts. However, the mechanism was not recognized at the time and the project team concluded that EGR must have caused the problem. No systematic testing of the UPS duty cycle was performed for this system.

When the second filter system incorporating electrically heated filters failed, the project team started to investigate more closely how the UPS vehicle was used. Cummins had performed extensive testing of this unit on the Green Truck and had not uncovered any problems. Failure when tested on the UPS vehicle was a surprise. It was this failure that uncovered the differences in what was simulated by testing the Green Truck and actual UPS driving conditions. Table 5 indicates portions of the duty cycle that were tested with the Green Truck for each filter system. The project team did not start to simulate engine restarts until the third system and then only limited.

Table 5. Duty Cycle Tests Performed on Filters Installed on the Green Truck

No.	Filter System	Duty Cycles Tested			
		Freeway	Surface Streets	Stop & Go Acceleration	Key-off Restart
1	Ibiden single filter	✔	✔	Limited	—
2	Ibiden dual, heated filter	✔	✔	Extensive	—
3	6.5L Cordierite	✔	✔	✔	Limited
4	Metallic	✔	✔	Extensive	Extensive

Once it was determined that filter cell density was an important variable regarding face plugging, it then followed that engine restarts could be a major contributor to plugging. Cummins testing of the 6.5L cordierite filter with reduced cell density confirmed this hypothesis.

The experience with these filter systems indicated the importance of optimizing trap cell density and trap capacity to engine and fuel conditions. It was also important to consider how the duty cycle affects filter system performance. In the case of the two Ibiden designs, Cummins and Rhodia concluded that the cell density was too high for the turbocharged, EGR-equipped 5.9L engine. The amount of unburned fuel during startup requires that the trap cell density be decreased to eliminate face plugging. Face plugging is further complicated by the UPS duty cycle, which requires 85 to 100 engine off-restart events during each day. Sizing of the trap is also important, and depends on how many times during the day that regeneration is required. This, in turn, depends on the engine loading so that exhaust temperatures compromise vehicle performance. If the duty cycle does not include at least some high engine loading, regeneration temperatures will never be achieved. The design of this system, therefore, requires careful integration of engines, fuel, filter cell density and size, and vehicle application. The extent of this integration was unknown at the beginning of this project.

4.3 Field Test

4.3.1 Objectives and Scope of Field Testing

A 1-year field test with two package cars equipped with the experimental engine and particulate filter systems was originally planned. The field test was intended to evaluate the fuel economy, reliability, maintainability, and performance of the engine-filter system. Field test data were to be collected from several sources, including:

- The on-board data loggers installed in the test vehicles
- Records of maintenance performed by UPS mechanics, obtained from UPS vehicle maintenance database
- Mileage accumulation and fuel fill data recorded daily by UPS personnel
- Records of installation, modification, or maintenance work performed by Cummins, Arthur D. Little, or their subcontractors
- Wear measurements performed on various engine components before and after the field test, to establish engine wear rates

To facilitate evaluation of the operating data from the test vehicles, operating data from two control vehicles in similar service were to be recorded. The control vehicles were to be identical to the test vehicles, except that the controls would be equipped with 160-hp mechanically-controlled Cummins B5.9 engines instead of the 175-hp test engine. As a result of the performance problems encountered with several filter configurations, the actual field testing effort was not as extensive as planned. The test vehicle at UPS was operated for a total of 11 months, and was operated in conjunction with only one conventional control vehicle. The control vehicle was UPS delivery van No. 650605. Cummins' Dodge Ram (the Green Truck) saw approximately two months of operation at Columbus, Indiana, during development and testing of filter systems for the project.

4.3.2 Description of the Host Site and Test Vehicle Service Route

The test vehicle, UPS delivery van No. 650604, serves a route that travels from the San Bernardino depot, to locations high in the San Bernardino Mountains. The route is shown by the heavy black line in Figure 15. A detailed route description appears in Table 6.

The test vehicle's route has a round trip distance of about 125 miles. The driver makes various side trips for pickups and deliveries in the area between the intersection of SR 38 and Valley of the Falls Drive, and the northern end of Baldwin Lake. Depending on the number of pickups and deliveries that the driver makes, total daily mileage may be as high as 170 miles.

This route involves steep climbs and descents, as shown in Figure 16. Beginning from the UPS depot at 1,050 feet MSL, the route climbs to approximately 6,300 feet at the end of Valley of the Falls Drive. The driver then turns around and descends back to the intersection of Valley of the Falls Drive and SR 38, at an elevation of 4,500 feet. After the intersection, the climb up SR 38 toward Baldwin Lake tops out at 8,800 feet, near

Sugarloaf Mountain, then descends to 6,600 feet at the shore of Baldwin Lake. This profile is then reversed on the inbound trip to the depot, except for the climb up Valley of the Falls Drive, which is made only if a pickup is requested on the inbound trip.

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Figure 15. UPS Test Vehicle's Service Route

Table 6. Service Route of the UPS Test Vehicle

From the UPS depot on Victoria Avenue, head west for a block. Turn left (Southbound) on Tippicanoe Avenue. Proceed South on Tippicanoe to intersection with Interstate 10. Head East on Interstate 10. Exit at N. University Street in Redlands. Proceed North on N. University Street until it intersects with State Route (SR) 38. Turn right (eastbound) on SR 38. Proceed east on SR 38 until it intersects with Valley of the Falls Drive. Follow Valley of the Falls Drive as it climbs up Mill Creek Canyon, and dead-ends in the community of Forest Falls. Turn around at end of Valley of the Falls Drive, and proceed back to intersection with SR 38. Turn right on SR 38 at the intersection. Follow SR 38 through the towns Angelus Oaks, Barton Flats, Lake Williams, and Sugar Loaf. Near the South shore of Baldwin Lake, turn right on to E. Shay Road. Proceed East and North on E. Shay Road, to its intersection with SR 18, at the North end of Baldwin Lake. At intersection, turn around and return home by same route as outbound trip. Bypass the side trip up Valley of the Falls Drive, if no pickups are needed there.

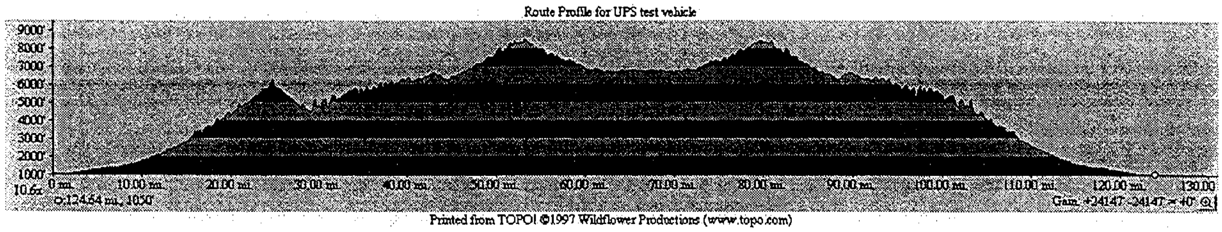

Figure 16. Topographic Profile of UPS Test Vehicle's Service Route

4.3.3 Field Test Data Collection

During field testing, operating data from the test and control vehicles were collected from three sources:

- Manually recorded mileage accumulation and fuel consumption data
- The data logger installed in the test vehicle
- Maintenance records

UPS personnel kept daily records of mileage accumulation between fuel fills and fuel fill volume for both the test vehicle and the control. These data were recorded during the period of late October 1998, through the end of April 1999.

Rhodia personnel regularly downloaded operating data from the data logger installed in the UPS test vehicle. The data logger's cellular modem allowed this to be performed remotely via a telephone line. These data were used to diagnose engine and filter condition. Integrating the speed-versus-time data allowed mileage accumulation of the test vehicle to be estimated during the period of July 1 – August 31, 1999. The control vehicle was not equipped with a data logger.

UPS records all maintenance activity in a vehicle maintenance database, stored in their computer network. Each record stored includes a description of the work performed and the labor and parts costs incurred. Arthur D. Little, Cummins, and Rhodia personnel kept manual records of the work they performed.

4.3.4 Field Test Results

A number of tests were performed on the UPS control and test vehicles. A data logger was installed for a limited period on one control vehicle to get information on the UPS duty cycle. Four filter concepts were also tested; two at the host site as described in the previous section and below. The project team also tested the cerium dosing system. Mileage accumulated and fuel economy were also recorded for the test and control vehicles.

Figure 17 shows the timing of these various tests and puts this testing in perspective with the filter system development discussed in the previous section. After the failure of the first Ibiden filter system, Cummins needed three months to specify, assemble, and

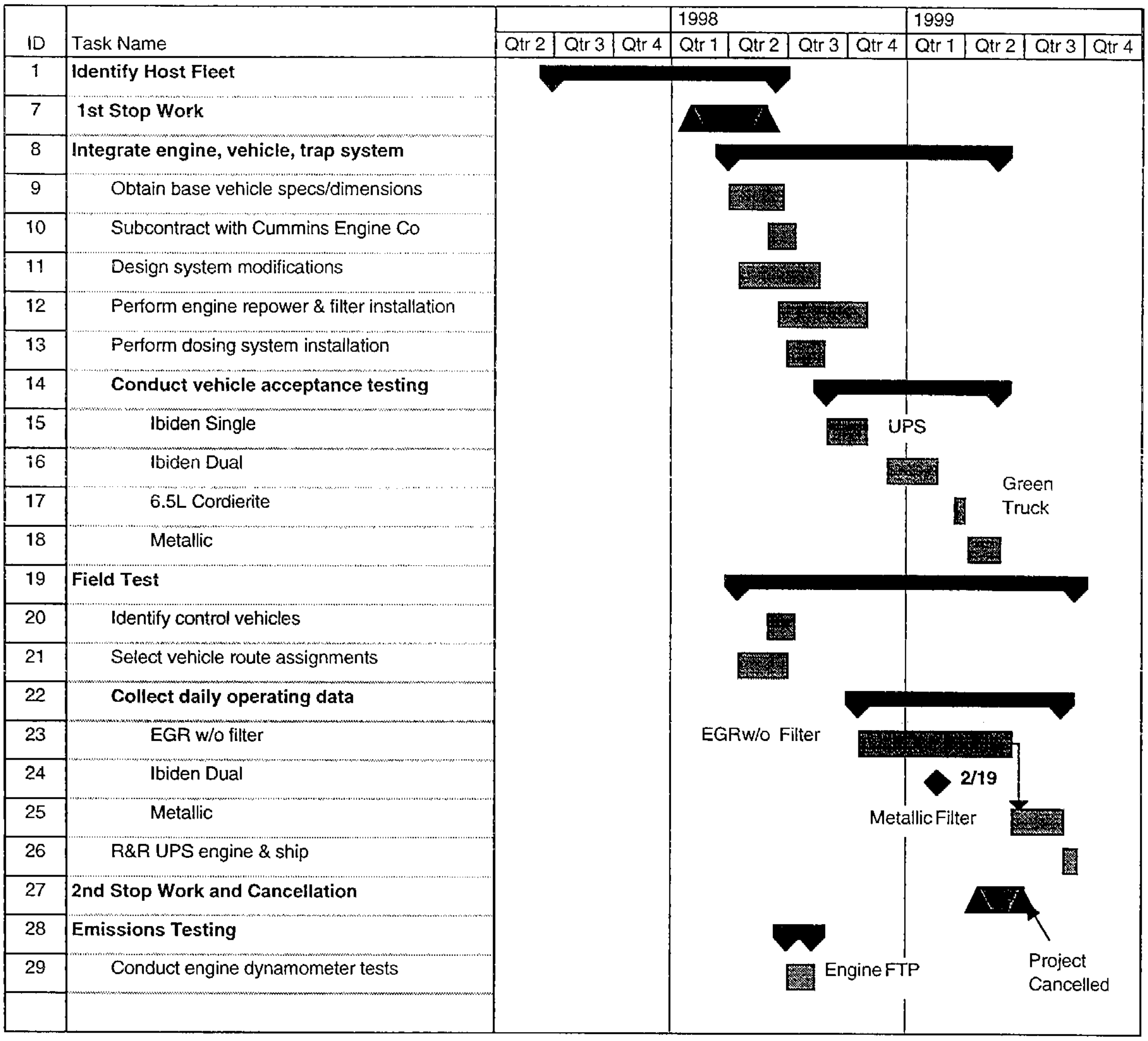

Figure 17. Project Timeline for EGR-Filter System Development and Testing

test the electrically heated filter system. During this time, the project team agreed that it would be useful to begin field testing with the test engine operating without a particulate filter. This would enable the engine and cooled EGR system to accumulate as many operating hours as possible, which would provide more experience to evaluate the performance of the EGR system and its impact on engine wear rates. The test vehicle was shipped from Columbus, Indiana, to UPS's San Bernardino Depot on October 19, 1998. It began field testing service on the following day.

While the UPS test was underway, the project team continued to investigate hardware solutions to filter face plugging. As indicated on the schedule, work on the Ibiden dual filter system started in November 1998 and ran through February 1999, when the system was installed on the UPS truck during the week of February 15, and field tested on February 19, 1999. After the failure of this system in the field, the project team worked on testing the lower density cordierite filter that led to specifying and testing the metallic filter. Developmental testing of the metallic filter started in April 1999 and was completed by mid-May 1999. The metallic filter was installed on the UPS vehicle in June and operated through August.

The remainder of this section discusses the field testing performed on the UPS test vehicle.

Instrumentation of Control Vehicle

While engine and particulate filter installation was proceeding with UPS package car No. 650604 at Cummins, Rhodia and Arthur D. Little made arrangements to obtain baseline duty cycle and performance data on a control vehicle in the test vehicle's service route. The project team wished to know what sorts of loads, thermal excursions, and frequencies of starts would be encountered in service. Therefore, the control car, UPS 650605, was instrumented with the SwRI data logger and monitored in service for several days. Data logger installation was completed on September 2, 1999; approximately 5 service days of data were recorded. These data indicated that the route entailed frequent starts (80 to 100 a day), and considerable low-speed operation. However, high exhaust temperatures were developed daily during the 40-minute climb to the delivery area. Although this route was a very demanding stop-and-go duty cycle, the project team considered the characteristics of the route sufficient to assure reliable daily particulate filter regeneration.

At this time, the project team did not realize the impacts of the significant number of engine restarts. Instead, we focused on whether the exhaust temperatures would be sufficient to result in daily filter regeneration.

Field Testing of Filter Systems

First System – Single 3L Silicon Carbide

As the single, unheated silicon carbide particulate filter system exhibited severe, uncontrollable plugging during initial performance evaluation with the UPS package car, it was considered unsuitable for field testing, and was removed before the vehicle was returned to service.

Second System — Heated Twin 6L Silicon Carbide

Components of the second particulate filter system were shipped to the San Bernardino UPS depot in early February 1999. Engineers from Ibiden installed and tested the face heating system and butterfly valve controller. An engineer from SwRI adapted the on-board data logger to record filter temperatures at the front, center, and rear of both filter elements. Cummins supervised the installation of the heavy-duty (250A) alternator needed for the face heaters, fabrication of a modified exhaust system at a muffler shop in San Bernardino, and installation of the entire filter system. Installation of the twin filter system was completed on February 17, 1999. The UPS package car went on its service route on February 19, 1999. The vehicle performed well during the climb from the San Bernardino depot to Big Bear. The package car climbed at highway speeds, and exhaust temperatures were high. Rhodia personnel accompanied the driver, and observed from the data logger output that a regeneration took place during the climb.

However, the vehicle began to perform poorly soon after it started making delivery stops. The engine ran roughly, with reduced power. The driver was able to complete his deliveries and bring the vehicle back to San Bernardino without opening the manual filter bypass, but it was obvious the filter system was not functioning correctly. Preliminary analysis indicated that the butterfly valve controller might have malfunctioned.

The vehicle was taken out of service to further diagnose this assessment on February 20, 1999. Cummins performed the diagnosis, and found that the filter regeneration control system and valves worked fine. Cummins then disassembled both filter systems with the assistance of engineers from Ibiden. Heavy deposits were observed on the face of each filter. The reasons for these deposits were unknown at that time, so it was decided to reinstall the package car's original muffler, and return the vehicle to regular service. The package car continued to serve with the test engine without a particulate filter during the period of February 22, 1999, through mid-June 1999, when the 19L metallic filter was installed.

Subsequent analyses of filter face plugging pointed to unburned fuel coking on the face of the filter, as a result of the many engine restarts during the UPS delivery route. During starts, the engine is overfueled. This overfueling leads to unburned fuel coking on the filter face. It was initially speculated that this problem might have been exacerbated by high altitude, as the delivery area at Big Bear is more than 6,000 feet in elevation.

Both Cummins and Rhodia believed that the best solution was to switch to a filter with lower cell density. Both the single, unheated 3L filter and the heated twin 6L system had a cell density of 300 cells/in^2. By reducing the cell density, the tendency of the unburned fuel deposits to plug the face would be diminished. Cummins and Rhodia recommended testing a 100 cell/in^2 cordierite filter, and then, if necessary, a larger filter with an even wider frontal opening using a metallic substrate.

Fourth System Metallic Filter

Based on the success of testing this filter on the Green Truck, Arthur D. Little, Cummins, and Rhodia recommended that the HJS filter be installed and tested in the UPS package car.[8] Cummins and Rhodia installed the HJS filter in the UPS vehicle in late June 1999. It was operated in delivery service during June 30 – August 31, 1999. During this time, UPS personnel added measured doses of EOLYS to the fuel tank manually, during fueling. No face plugging or regeneration problems occurred with this

[8] Michael Jackson, Arthur D. Little, Inc., *Recommendations for Completing Rhodia Project,* memorandum to Chris Abe of SCAQMD and Tony Andreoni of ARB, dated 19 May 1999.

filter. Approximately three drivers were assigned to the vehicle during this time. A driver who operated the package car for a week while the primary driver was away on vacation reported that engine performance became sluggish in the afternoon. DPF loading and backpressure likely increased each day during the frequent stops and low speeds in the delivery area. He apparently drove the car hard for several minutes when this occurred, which successfully initiated regeneration.[9] Exhaust backpressure data showed a regular pattern of a slow rise followed by a more rapid decline, indicating that soot was accumulating and then burning (Figure 18). The filter routinely regenerated during the daily trip from the depot to the delivery area, and on the return.

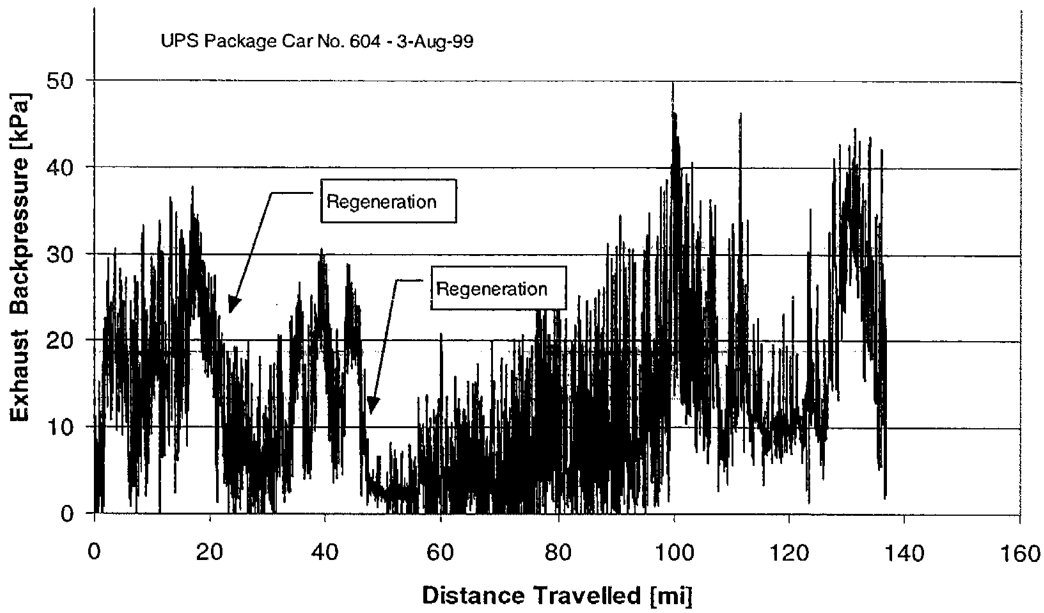

Figure 18. HJS Trap Regeneration Behavior in Service

Tests of On-Board Fuel Task Dosing System

The fuel tank dosing system was installed on the UPS test vehicle as part of the first Ibiden filter system. Its operation was vertified at Cummins. When the project team decided to ship this vehicle to UPS to operate with the advanced EGR engine only, this system was disabled. We did not want to add cerium to the diesel fuel without having a filter in place to collect particulate emissions.

In early February 1999, Arthur D. Little personnel reconnected the on-board EOLYS dosing system, in order to test its functionality before the electrically heated twin filter system was installed. Arthur D. Little collected several fuel samples from the test

[9] e-mail memorandum from Oliver Touret of Rhodia Rare Earth's to Michael Jackson of Arthur D. Little, dated 12 July 1999.

vehicle's fuel tank, and sent them to Rhodia for analysis. The dosing system was supposed to maintain a 50-ppm cerium concentration in the fuel.

The analyses indicated that no cerium was present in any of the fuel samples. A display in the vehicle from the dosing pump controller indicated that the controller was commanding the pump to stroke, yet no cerium had been delivered to the fuel tank. This analysis was not completed until *after* the electrically heated filter system had failed due to face plugging. Tests on the heated filter were performed with the assumption that the analysis would show that the dosing system was working properly, when, in fact, no EOLYS was present in the fuel. Nevertheless, the project team agreed that the face plugging of the heated filter system was so rapid and severe that the presence or absence of EOLYS would not have materially affected the system's performance.

Following the fuel analysis, Arthur D. Little personnel removed the EOLYS tank and dosing pump, and returned it to Walbro Corporation for analysis. Walbro reported that they found the cause of the dosing system malfunction. The EOLYS tank was full, and showed no evidence of leakage. The dosing pump was removed and tested, and functioned normally. However, while testing continuity through circuits of the dosing system's controller, high resistance was observed in one of its connectors. The connections to the controller were crimped and then potted in silicone. Walbro removed the potting material and tested the crimps. Three of them were quite loose. It appeared that several of the connections were not sealed or crimped well. Moisture, clay, and, possibly, road salt apparently leaked into the connection and corroded the wires, causing them to eventually fail. The dosing tank was installed in the vehicle next to the lower left side of the radiator. Walbro said that the underhood area where the dosing system was located was surprisingly dirty.

Mileage Accumulation and Fuel Economy

During October 20, 1998 through February 5, 1999, the UPS package car was operated with the ISB engine equipped with cooled EGR, but without a particulate filter system. During this time, the EOLYS dosing system was disconnected, to prevent exhaust emissions of cerium oxide from the unfiltered exhaust system. As indicated in Figure 19, the test vehicle accumulated mileage at a higher rate than the control vehicle during this time. The vehicle required no road calls and received only normal scheduled engine maintenance. Drivers reported that they enjoyed driving the test vehicle, as its higher horsepower (175 bhp versus 160 bhp for the rest of the diesel fleet) gave it noticeably better performance when climbing grades. An electrically heated dual particulate filter system was installed in the vehicle in mid-February 1999. The vehicle operated only one day with the electrically heated particulate filter, however, due to severe face plugging. Cummins subsequently removed the particulate filter system, and the vehicle resumed service unequipped with a filter on February 23, 1999. It continued operating in this mode through mid-June 1999.

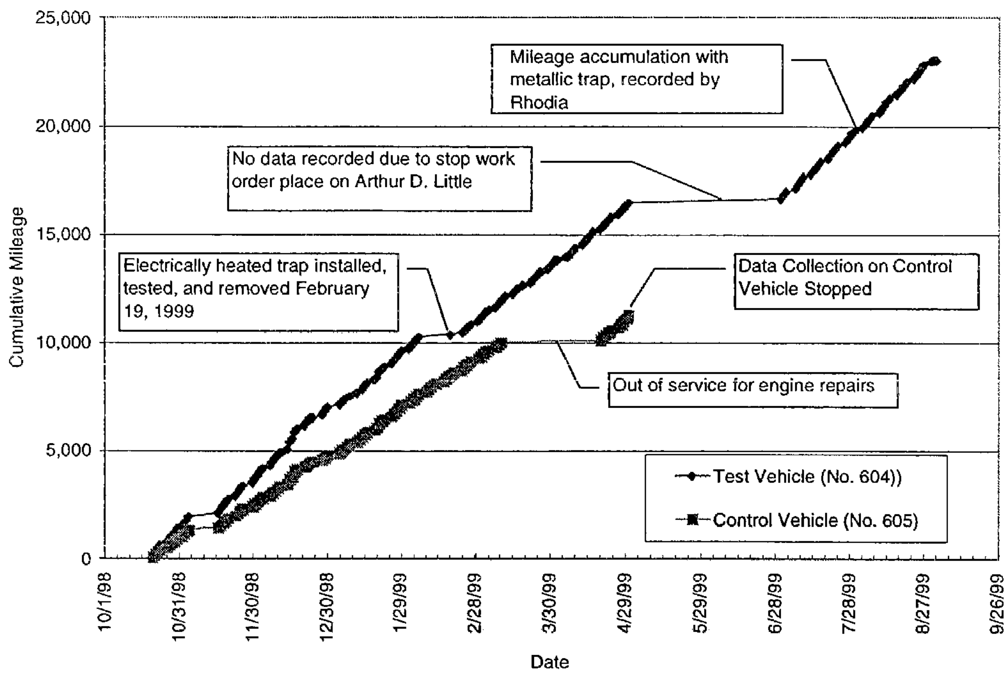

Figure 19. Mileage Accumulation Recorded by UPS Test and Control Vehicles

In mid June the metallic filter was installed on the UPS vehicle and the vehicle successfully operated until the end of August 1999. Cummins then removed all test hardware from the vehicle and restored the vehicle to its original configuration.

Despite developing higher horsepower than the control vehicle's engine, the test engine recorded significantly lower fuel consumption than the control. This is shown by plots of the two vehicle's cumulative average[10] fuel economy (Figure 20). As of February 5, 1999 (shortly before the time that the heated dual filter system was installed), the test vehicle recorded an average fuel economy of 8.87 mi/gal, while the control vehicle recorded 6.32 mi/gal. Fuel consumption by the test vehicle was 28 percent lower than that of the control vehicle. The control vehicle showed a downward trend in fuel economy during October – February 1999, possibly indicating that its engine was drifting out of adjustment. This may have contributed to the large observed difference in fuel economy.

[10] "Cumulative average" refers to the average of the time between the start of field testing and the date of the fuel economy datum.

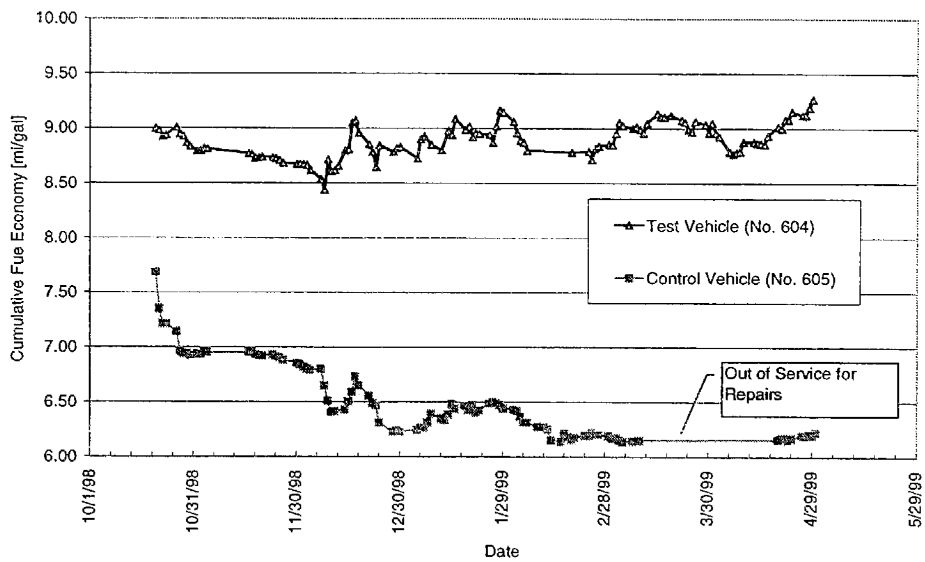

Figure 20. Cumulative Average Fuel Economy

4.4 Wear Measurement Results — Implication for the Engine Durability

Prior to modifying the 5.9L engines with the EGR systems, these engines were torn down; and parts with wear surfaces, such as the piston rings, crossheads, and valve tappets, were weighed, in order to establish wear rates when the parts were re-weighed after field testing was concluded. Similarly, intake and exhaust valve recession was measured with valves assembled in the head.

Cummins disassembled the test engine from the UPS vehicle after the field test was completed, and performed several measurements of components subject to wear. Technicians weighed the piston rings and crossheads before the engine entered service, and again, after teardown. This enabled the rate of material loss to be estimated. A summary of these wear measurements appears in Table 7.

Three cylinder assemblies were equipped with CKS top rings, and three with chrome rings. The CKS rings were machined from a proprietary hardened alloy, and were installed to investigate their wear resistance compared to that of chrome. The wear data show that the CKS rings exhibited substantially less wear area, depth, and material loss than the chrome rings. Cylinder bore wear was lower with the CKS rings as well. Overall, the wear data support the conclusion that engine wear rates in the test engine was substantially higher than in a production California-model ISB engine with EGR. The elevated wear rates likely result from the higher rates of EGR employed in the test engine compared to the production-model engine, and the use of EGR cooling promotes the formation of nitric acid and sulfuric acid via reactions between water vapor and nitrogen oxides and sulfur oxides in the exhaust gas. These acids promote corrosion of the ring and cylinder surfaces.

Table 7. Test Engine Wear Measurements[11]

ISB UPS Engine 56432328				
Component Measurements after 29,000 Miles of Use				
	Ave. Wear Area (mm^2)	Ave. Wear Scar Depth (mm)	Ave. Weight Loss (gm)	Recession Increase (in.)
Top rings				
CKS	0.006	0.005	0.076	
Chrome	0.017	0.009	0.100	
2nd ring			0.082	
Oil ring			0.027	
Cylinder bores				
with CKS rings	0.036	0.008		
with chrome rings	0.039	0.009		
Crossheads			0.004	
Tappets			0.138	
Intake valve				0.0003
Exhaust valve				0.0001

4.5 Emission Testing

As indicated in Section 3, the intent of this testing was to characterize the emissions of an advanced diesel engine system. The project team and sponsors were interested in both the regulated emissions as well as other emissions that may be an issue with these advanced systems. With this in mine, the project team proposed both engine dynamometer testing prior to and after the demonstration to characterize regulated emissions over the demonstration period. Chassis testing was also proposed to assess in-use emissions of both regulated and unregulated emissions. These tests would be performed during the course of the demonstration.

As the project focused more on developing the EGR-filter system, less effort was placed on characterizing the emissions of the system. However, Cummins performed one FTP transient, engine dynamometer test (following the guidelines of Code of Federal Regulations 40 CFR Part 86). The results of this test and additional emissions data supplied by Rhodia are discussed in this section.

[11] Data provided by A. S. Ghuman, Executive Director, Advanced Product Development, Cummins Engine Company, May 2000. No comparison to California ISB wear data are shown since Cummins considers these data proprietary.

4.5.1 Cummins FTP Testing

Cummins developed a variety of EGR control schedules for the test engine to determine the relationship between EGR-on time and FTP NO_x rate. Cummins provided Arthur D. Little with emission testing results for three EGR schedules, plus results with EGR on at all times. Cummins also provided certification test data for the production model 1998 ISB engine, rated at 175 bhp. Emission test data are presented in Table 8.

Table 8. Low-Mileage FTP Emissions Test Results

Configuration	Relative NO_x (%)	Transient Cycle (g/bhp-hr)			
		NO_x	HC	NO_x + HC	PM
Production ISB engine with no EGR, 2,354 rpm EPA-rated speed	Baseline	3.78	0.15	3.93	0.11
First EGR control setting, 2,364 rpm EPA-rated speed	72	2.74	0.13	2.87	<0.03
Second EGR control setting, 2,364 rpm EPA-rated speed	68	2.56	0.13	2.69	<0.03
Third EGR control setting, 2,364 rpm EPA-rated speed, particulate filter not installed	67	2.53	0.12	2.65	0.14
Third EGR control setting, 2,364 rpm EPA-rated speed – delivered configuration	**67**	**2.53**	**0.12**	**2.65**	**<0.03**
No EGR control (EGR on continuously), 2,354 rpm EPA-rated speed	62	2.33	0.12	2.45	<0.03
Third EGR control setting, 2,500 rpm EPA-rated speed	62	2.33	0.14	2.47	<0.03

Notes: Engines are rated at 175 bhp at 2,364 rpm. Intake restriction for all configurations = 20 ±1 in. water gauge; exhaust restriction = 2.2 ±0.2 in. Hg. All configurations except the production ISB engine were equipped with cooled EGR, EOLYS fuel-born catalyst, and Ibiden 3L silicon carbide diesel particulate filter with 300 cells/in^2. PM measurements limited by instrumentation accuracy and actual values could be lower than the 0.03 g/bhp-hr upper bound.

The results indicate some sensitivity to EGR control with NO_x emissions varying from 2.74 g/bhp-hr to 2.53 g/bhp-hr. With EGR on continuously, the NO_x level was dropped to 2.33 g/bhp-hr. One test was also performed without a filter indicating the NO_x-PM tradeoff. In this test NO_x was reduced from 3.28 to 2.53 g/bhp-hr and particulates increased from 0.11 to 0.14 g/bhp-hr compared to the baseline 1998 ISB engine.

The final calibration chosen was the "third EGR control setting" which is indicated in bold in Table 8. This configuration produced the following results:

	Results in g/bhp-hr Compared to Baseline	% Reduction
HC:	0.15 vs 0.12	20
NO_x:	3.78 vs 2.53	33
PM:	0.11 vs 0.03	73

A comparison between the baseline and five calibration results is also shown in Figure 21.

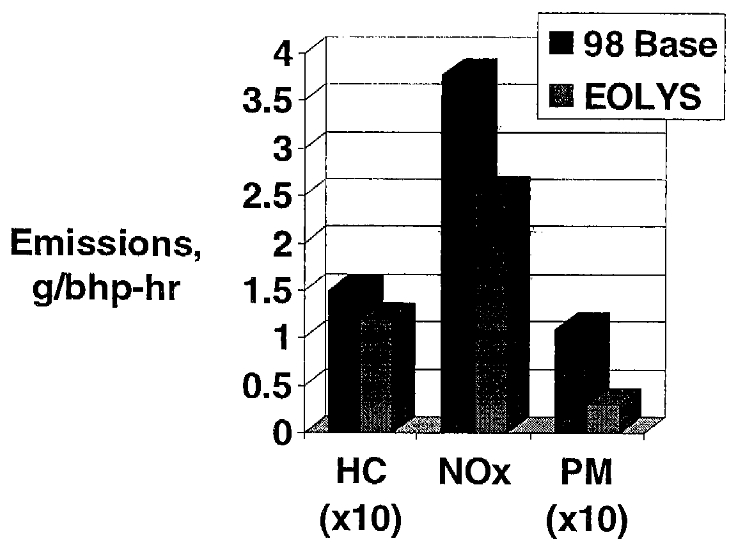

Figure 21. Comparison of FTP Engine Emissions Results

All of these results were obtained with the single Ibiden filter system (3L silicon carbide filter). Emissions testing were not performed on the metallic filter, which was the only system to successfully operate in UPS service. Nevertheless, the results for the Ibiden system should be comparable to the metallic filter. The pressure drop was comparable; therefore, we do not expect any effect on NO_x emissions. Particulate filter performance should be at least as good with the metallic compared to the silicon carbide filter. Filter efficiencies above 80 percent have been achieved for a variety of filter media in many tests reported in the literature.

Hydrocarbon reduction most likely would be affected by filter material and manufacturing technique. This reduction is due to oxidation in the filter and will be effective by filter materials, construction, and interactions with the cerium additive.

4.5.2 Dioxin and Furan Testing Data Sponsored Separately by Rhodia

Rhodia Rare Earth's has co-sponsored recent research into the effect of cerium catalysts on regulated and toxic emissions from diesel engines. This work was conducted by N. V. Heeb at the Swiss Federal Laboratories for Materials Testing and Research (EMPA). The work included exhaust emission testing with a modern European turbocharged, aftercooled, and direct-injected diesel engine (Liebherr Type 924 TI, 6.6L), operating with and without a sintered metal diesel particulate filter. Heeb investigated emissions using reference diesel fuel, as well as fuels treated with iron, copper, and cerium catalysts. The results of this work have been published previously.[12]

The results of the EMPA testing showed that particulate trap technology substantially reduces particulate emissions (88 to 95%). Fuel additives such as cerium reduced PM by 19 to 29% without a trap. Further trap technology also substantially reduced the emissions of polycyclic aromatic hydrocarbons (PAHs) that are bound mainly to diesel soot. CO emissions increased by some 16 to 40% with traps irrespective of the additives in the fuel. Total hydrocarbons were reduced by 30 to 50%, but it was found that volatile organic compounds (VOCs) increase. EMPA saw increases in 1,3-butadiene, formaldehyde, and acetaldehyde.

Using diesel fuel without detectable chlorine content (<2 ppm), no detectable increase in emissions of polychlorinated dibenzodioxins/furans were measured compared to background levels. Additionally, EMPA found that the use of either iron or cerium fuel additives did not increase the polychlorinated dibenzodioxins/furans emissions.

4.6 Cost Estimate and Future Technology Outlook

Although a detailed cost estimate was not performed, we estimate that the cooled EGR system, on-board EOLYS dosing system, and particulate filter investigated in this project would increase the cost of a current model Cummins ISB engine by about 20 percent. In addition, the cerium additive is estimated to cost an additional 5 percent over diesel fuel prices.

The emerging conventional approach to diesel emission control will most likely consist of a combination of high-pressure fuel injection, variable-geometry turbocharger, cooled EGR for NO_x reduction, and an oxidation catalyst for PM reduction. These features are present in Detroit Diesel's recently announced Series 50 transit bus engine, which will be certified to 2.5 g/bhp-hr NO_x and 0.05 g/bhp-hr PM.

After 2007, legislated NO_x and PM standards will be sufficiently stringent to necessitate the wide use of DPFs and the combination of other NO_x technologies. The EPA will likely implement its planned 15-ppm sulfur standard for on-road diesel fuel. This standard would reduce sulfur concentration considerably from the current limit of 500

[12] N. V. Heeb, Swiss Federal Laboratories for Materials Testing and Research (EMPA), *Influence of Particulate Trap Systems on the Composition of Diesel Engine Exhaust Gas Emissions (Part II)*. Dübendorf, Switzerland, July 1998.

ppm.[13] The reduction is intended to enhance the use of catalyzed regenerating particulate filter technologies. If the lower sulfur level enables catalyzed particulate filters to be adequately durable, vehicle manufacturers would probably consider them preferable to more complex fuel-borne catalyst systems. However, it should be noted that even with ultra-low diesel fuel (<10 ppm) as used in Sweden, these catalyzed regenerating filter technologies have been unable to fulfill European passenger car requirements for trap regeneration in all driving conditions, thus confirming the need for system integration in such cases as the Peugeot 607 HDi sedan application.

The positive aspect of fuel-borne catalyst technology is that when system integration is performed, it will achieve regeneration in all driving conditions. The drawback is complexity, but every system is necessarily complex to address such issues.

[13] "Range of Technologies will Help Diesel Survive Emissions Challenges," *Diesel Progress, North American Edition*, June 2000.

5. Conclusions

The objective of this work was to demonstrate the in-use viability of an advanced diesel engine. Due to a variety of issues related to the performance and readiness of the technology, this objective was not achieved. Cummins and Rhodia designed and developed the advanced diesel system that included cooled EGR, cerium-based fuel additive, and a DPF. The system was integrated into a Cummins 5.9L, B Series diesel engine.

The advanced 5.9L engine system was installed in an UPS package car and tested. Several DPF trap concepts were investigated to solve filter face plugging. Eventually, one system was successfully demonstrated. The successful system used a metallic trap with larger frontal face openings (effectively reducing the trap density). This system was not optimized but worked over the demanding UPS duty cycle.

The EGR engine without a DPF or fuel additive operated quite reliably in service, accumulating more than 24,000 miles in less than 12 months despite outages due to equipment retrofits. Also, the engine DPF system achieved low NO_x and PM emissions targets of 2.5 g/bhp-hr and less than 0.03 g/bhp-hr, respectively. Nevertheless, even with the commitment of all team members, this technology needed substantially more development and integration to meet the demanding stop-and-go duty cycle operated by UPS. Numerous hot restarts and low-speed engine operation make the UPS duty cycle extremely challenging for EGR-DPF technology. Following are the project team's conclusions regarding this technology.

Rigorous application engineering and system integration are needed in order for this system to eliminate DPF face plugging and achieve regeneration, especially in stop-and-go duty cycles characterized by numerous hot restarts and low engine loads.

With a cooled EGR system, properly optimizing particulate filter density and volume is very important for successful filter operation. Filter elements with cell densities that are too high are subject to rapid face plugging. EGR rate is, in effect, controlled by filter backpressure; excessive backpressure causes very high EGR rates, along with poor engine operation. Control to limit the EGR rate, and to perform EGR integration taking into account the backpressure created by the DPF, may be necessary.

With careful matching of trap characteristics to the vehicle application and system integration design, the combination of cooled EGR, EOLYS fuel-borne catalyst, and a particulate filter is feasible for reducing NO_x and PM rates in heavy-duty diesel vehicles. However, significant engineering and system control are necessary to achieve an operating system. Further, no conclusions can be inferred regarding the reliability or durability of this technology in use. Not enough experience with the metallic trap was obtained.

A lot more optimization of the metallic filter is needed before this system could be commercialized. Filter size would be reduced based on considerations of duty cycle and expected exhaust temperatures. The use of a 19L-size filter for the project was based solely on availability of a metallic filter from HJS.

Previous testing by Czerwinshke, et al. has indicated that filters are an effective technology for reducing ultrafine PM emissions. Filters seem to be equally effective across the entire particulate size distribution. Further, based on the testing of Heeb, there does not appear to be any unregulated emissions surprises. Heeb presented evidence of reduced PAHs and no detectable increased emissions of polychlorinated dibenzodioxins or furans.

The biggest drawback to passive trap technology is that it will not regenerate reliably in some operating modes. Regardless of the regeneration technology applied, there is no way of continuously burning PM in driving cycles with a large proportion of low-load and/or frequent stop-and-go duty cycles with frequent hot restarts. Fairly frequent and sustained intervals of high engine load are needed, with good control of the regeneration in order to avoid filter plugging.

Rhodia has recently commercialized EOLYS in Europe in Peugeot diesel-passenger cars. In this application, the particulate filter is integrated into a system including the EOLYS on-board dosing system, engine management, common rail injection with a possibility of post-injection, oxidation catalyst for cold start and burning of the post-injected hydrocarbon, and a silicon carbide DPF. When engine loads are not sufficiently high to allow continuous regeneration when required by DPF backpressure, the system initiates regeneration using engine management and post-injection strategies. This commercial application is working with the current sulfur content in European diesel fuel. Lowering sulfur content will make the system more efficient and durable, but it is not a requirement. Rhodia believes a similar arrangement is necessary for heavy-duty vehicle applications.

Glossary of Terms, Abbreviations, and Symbols

A	=	amp
ARB	=	California Air Resources Board
bhp	=	brake horsepower
cells/in^2	=	cells per square inch
CeO_2	=	oxidized to ceria
DPF	=	diesel particulate filter
EGR	=	exhaust gas recirculation
EOLYS	=	Rhodia's cerium fuel-borne catalyst and filter system
EMPA	=	Swiss Federal Laboratories for Materials Testing and Research
EPA	=	U.S. Environmental Protection Agency
FTP	=	Federal Test Procedure
ft	=	feet
ft-lb	=	pound(s) per foot
g/bhp	=	grams per brake-horsepower
g/bhp-hr	=	grams per brake-horsepower per hour
gm	=	grams
GVWR	=	gross vehicle weight rating
HDDE	=	heavy-duty diesel engine
Hg	=	Mercury
HJS	=	German Filter Manufacturer
in	=	inch
in. Hg	=	inches of mercury
in^2	=	square inch
in^3	=	cubic inch
ISB	=	Interact System B-Sries
km	=	kilometer(s)
kPa	=	Kilopascal (a pressure measurement unit)
L	=	liter
lb	=	pound
mi/day	=	miles/day
mi/hr	=	miles per hour
MHDDE	=	medium-heavy-duty diesel engine
mm	=	Micron(s)
mm^2	=	millimeters squared
MOU	=	Memorandum of Understanding
MY	=	model year
NGK	=	Japanese Filter Manufacturer
NOx	=	oxides of nitrogen
OCTA	=	Orange County Transportation Authority
PAH	=	polycyclic aromatic hydrocarbon
PM	=	particulate
ppm	=	parts per million
psi	=	pounds per square inch
RPM	=	revolutions per minute
rpm(t)	=	engine speed

SCAQMD	=	South Coast Air Quality Management District
SwRI	=	Southwest Research Institute
UPS	=	United Parcel Service
V	=	volt
VOCs	=	volatile organic compounds
VIN	=	vehicle identification number
v(t)	=	vehicle velocity
VDC	=	volts DC
°C	=	degrees centigrade